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FORMING TEST FOR TRANSPARENT PLASTIC SHEET MATERIALS

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WRIGHT AIR DEVELOPMENT CENTER

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FOREWORD

This report was prepared by the Rohm and Haas Company, under USAF Contract No. AF 33(038)-22945. The contract was initiated under Research and Development Order No. 616-12, "Transparent Materials", and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Lt W. K. Stemple acting as project engineer.

ABSTRACT

Development of a test procedure and apparatus for use in qualification testing of transparent plastic sheet material under military specifications is described. The procedure was used to differentiate the forming characteristics of five transparent plastic sheet materials that are supplied under five different Government Specifications for use in aircraft enclosures.

The plastic materials were found to be sufficiently different in characteristics at high temperatures to have distinctly different moduli of elasticity and to require different conditions of temperatures and pressures for forming. The forming parameters (thickness, pressure, time and temperature) which will permit qualification testing to differentiate the materials are given.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. E. SORTE
Colonel, USAF
Chief, Materials Laboratory
Directorate of Research

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INTRODUCTION

Various types of plastic materials are usable as transparent sections in aircraft enclosures. In general, these materials are manufactured as flat sheets which can be subsequently formed into more useful shapes for aircraft by the application of heat and a deforming load. However, not all such materials are formable into shapes involving compound curvature and certain of those materials which may be formed into compound curves are not as easily formable as others. Hence, there is a need for a method of test which will differentiate between the formability characteristics of the available transparent plastic materials for purposes of qualification testing under military specifications, which may be useful in the evaluation of new plastic materials and which will provide engineers with design criteria or limits of formability and extensibility. In addition, it is well known that inherent limitations of practical manufacturing techniques produce variations in all products. Thus, there is the possibility that the formability characteristics of a given type of transparent plastic material may vary with differences in manufacturing techniques.

The research reported herein is intended to devise a method of test of the formability characteristics of five plastic materials currently manufactured for use as transparent sections in aircraft enclosures. The method of test developed from this research:

1. Measures differences in the extensibility of the various materials under forming conditions.

2. Measures differences in the formability of the various types of plastic materials.

3. Is useful for specifying the formability of each type of plastic material.

OBJECT OF RESEARCH

THE PRIME OBJECT OF THIS RESEARCH WAS TO DEVISE A RELATIVELY SIMPLE PROCEDURE TO PERMIT QUALIFICATION TESTING OF THE FORMABILITY CHARACTERISTICS OF FIVE PLASTIC SHEET MATERIALS CURRENTLY MANUFACTURED FOR USE AS TRANSPARENT SECTIONS IN AIRCRAFT ENCLOSURES.

THE SECONDARY, CORRELATED OBJECTS OF THIS RESEARCH WERE:

A. TO DETERMINE THE FLEXURAL DEFORMATION VS. TEMPERATURE CHARACTERISTICS OF STANDARD SPECIMENS OF THE PLASTICS SUBJECTED TO VARIOUS STRESSES.

B. TO DETERMINE THE TENSILE MODULUS OF ELASTICITY VS. TEMPERATURE CHARACTERISTICS OF THE PLASTICS.

C. TO DETERMINE THE FORMING PARAMETERS (THE TIME, TEMPERATURE, LOAD, THICKNESS AND DEFORMATION RELATIONSHIP) REQUIRED TO PRODUCE OPTICALLY SATISFACTORY, APPROXIMATELY SPHERICALLY SHAPED SECTIONS FROM THE PLASTIC SHEET.

D. TO INVESTIGATE THE LIMITATIONS OF FORMABILITY OF THE PLASTIC SHEET WHICH COULD NOT BE SPHERICALLY SHAPED AND DETERMINE FORMING PARAMETERS FOR SUCH MATERIAL.

THE THIRD OBJECT OF THIS RESEARCH WAS TO DEVISE A SIMPLE TEST METHOD OR METHODS WHICH WILL POSITIVELY DIFFERENTIATE BETWEEN THE FORMABILITY CHARACTERISTICS OF THE SUBJECT PLASTIC MATERIALS.

SECTION II

APPARATUS USED

1. AN EXPERIMENTAL, CONTROLLED TEMPERATURE, FORCED CIRCULATION, AIR OVEN. ASSOCIATED EQUIPMENT AND A FIXTURE FOR SPHERICALLY FORMING 8" DIAMETER PLASTIC DOMES USING 11" DIAMETER DISCS.

FIGURE 1 IS A SCHEMATIC DIAGRAM OF THE EXPERIMENTAL OVEN ARRANGED TO MEASURE THE ELONGATION RATE OF PLASTIC SPECIMENS MAINTAINED AT A CONSTANT TEMPERATURE. FIGURE 2 IS A PHOTOGRAPH OF THE OVEN SET-UP USED TO MEASURE THE ELONGATION RATE. THE REMOVABLE PLATFORM SUPPORTS THE ENTIRE LOAD OF STRESSING WEIGHTS AND LOWER SPECIMEN TENSILE GRIPS UNTIL THE SUPPORTING LEGS OF THE PLATFORM ARE COLLAPSED WITH THE AID OF STRINGS.

As the platform drops, a microswitch on one of the platform guides starts the timer which is viewed by the 16 mm. camera with the aid of the mirror.

Figure 3 is a photograph of the tensile grips made to clamp hard or soft plastic specimens during elongation.

Figure 4 is a schematic diagram of the same oven arranged to measure the deformation of a plastic disc while being free-blown into a spherical section. The diameters of the sheaves were chosen to produce a movement of the armature of the motion sensor or transmitter (an inductance coil, see Reference 14) of 1.2" for a 4" vertical movement of the center of the test specimen. Movement of the armature is recorded by one of the pens of the recorder.

The controlled air pressure used to deform the test specimen into a spherical section was maintained at a constant value by a Model H-10 Conoflow Pressure Regulator. To avoid errors produced by air leakage, a completely separate air line (see Figure 4,) was used to connect the pressure indicators and recorder to the test jig. Figure 5 is a view of the air control side of the experimental oven. The small valve labelled "Clamping pressure control" controls the 80 to 100 psig. supply to the clamping pistons of the forming fixture. The pressure regulator provides air at 20 psig. to operate the indicators and recorder and also supplies air to the Conoflow pressure regulator used to provide constant pressure for forming test specimens. To obtain air pressure at the Conoflow regulator greater than 20 psig., a by-pass was provided from the supply line to the Conoflow regulator. This line appears below the filter in Figure 5. A pressure range change selector switch is used to direct the measured air pressure from the forming fixture to the proper pressure indicator which, in turn, operates the pressure recorder.

The temperature within the oven cavity is measured by the temperature sensing bulb (see Figure 7) and is recorded by one of the pens of the recorder.

The fixture or jig for forming spherical sections is shown disassembled in Figure 6 with a formed test specimen in place. The springs on the guide pins on the lower portion of the jig are used to support the weight of the top ring, hinged clamps and a flat plastic test specimen which is first attached to the top ring with spring-loaded paper clamps (not shown in the photograph). Thus, as the fixture is used in the oven, the horizontally moving air stream passes across both top and bottom of the test specimen during the preheating period.

THE AIR PRESSURE ACCUMULATOR, SHOWN IN THE OVEN CAVITY IN FIGURE 7, PROVIDES A RESERVOIR OF AIR AT THE OVEN TEMPERATURE AND AT A CONSTANT PRESSURE DETERMINED BY THE SETTING OF THE CONOFLOW REGULATOR. A SOLENOID VALVE RELEASES THE AIR IN THE ACCUMULATOR TO THE SPACE ENCLOSED BY THE TEST SPECIMEN AND THE BOTTOM PLATE OF THE FIXTURE TO START THE FORMING PROCESS. THE PRESSURE IS MAINTAINED BY AIR FROM THE CONOFLOW REGULATOR.

THE CLOCK WORK MECHANISM OF THE RECORDER WAS CHOSEN TO TURN THE CHART AT A RATE OF 1 REVOLUTION EVERY 6 MINUTES. THE ELECTRIC CURRENT ACTUATING THE SOLENOID VALVE IN THE AIR LINE ALSO SIMULTANEOUSLY STARTS THE CLOCK MECHANISM OF THE RECORDER.

2. BOLEX-PAILLARD 16 MM. MOVIE CAMERA EQUIPPED WITH AN F1.9, 26 MM. FOCAL LENGTH LENS.

3. NECESSARY GENERAL EQUIPMENT FOR TAKING, DEVELOPING AND PROJECTING 16 MM. FILM.

4. BAUSCH AND LOMB MICROSCOPE EQUIPPED WITH A MICROMETER EYEPIECE AND 48 MM. OBJECTIVE.

5. PRECISION SCIENTIFIC COMPANY "TIME-IT" TIMER NUMERICALLY INDICATING SECONDS AND 1/10 SECONDS.

6. FLEXURAL DEFORMATION (HEAT DISTORTION) TEMPERATURE TESTER (SEE REFERENCE 10).

7. MERCURY MANOMETER AND STANDARD GAGES.

8. NBS CERTIFICATE NO. 73075 -5°C. TO 360°C. (22°F. TO 680°F.) THERMOMETER.

9. ALNOR "VELOMETER" AIR VELOCITY METER.

10. BROWN "ELECTRONIK" 8 POINT TEMPERATURE RECORDING POTENTIOMETER AND THERMOCOUPLES.

11. HAZE METER (SEE REFERENCE 11).

12. FLOCKED-RUBBER COVERED CYLINDRICAL SECTIONS FORMS OF SEVERAL RADII.

SECTION III

MATERIALS

THE FOLLOWING SHEET PLASTIC WAS OBTAINED FROM THE INDICATED SOURCES. IN EACH CASE MATERIAL WAS ORDERED TO CONFORM TO THE PERTINENT SPECIFICATION, EXCEPTING FOR THE LUCITE, WHICH HAD BEEN PREVIOUSLY PURCHASED FOR OTHER PURPOSES, AND FOR SOME SHEETS OF PLEXIGLAS WHICH WERE NOT OF A THICKNESS APPEARING IN THE SPECIFICATION.

TABLE I

MATERIALS USED IN RESEARCH

Applicable Specification	Material Type	Nominal Thicknesses Obtained (Inches)	Trade Name	Source of Supply
MIL-P-6887	Acetate	0.060, 0.125	Lumarith	Celanese Corp. of America 12 South 12th Street Philadelphia, Penna.
MIL-P-6887	Acetate	0.125, 0.250	Plastacele	E. I. duPont Company Wilmington, Delaware
AF12041	Vinyl	0.060, 0.125 0.150	Vinylite	Bakelite Company 1649 N. Broad Street Philadelphia, Penna.
AF12040	Allyl	0.060, 0.125 0.250, 0.500	CR-39	The Homalite Corporation 13 Brookside Drive Wilmington, Delaware
MIL-P-5425	Acrylic	0.250	Lucite HC202	E. I. duPont Company Arlington, N. J.
MIL-P-5425A	Acrylic	0.250	Lucite HC212	E. I. duPont Company Arlington, N.J.
MIL-P-5425	Acrylic	0.060, 0.125 0.250, 0.500 plus various	Plexiglas II	Rohm & Haas Company Philadelphia, Penna.
MIL-P-6886	Acrylic	0.060, 0.125 0.250, 0.500 plus various	Plexiglas I-A	Rohm & Haas Company Philadelphia, Penna.

SECTION IV

PROCEDURE

CAMERA CALIBRATION

Lens resolution charts were taped to a vertical wall, along a horizontal and one diagonal line. The spacing of the charts was such as to subtend angles of 5°, 10°, 15° and 20° from the intersection of the two lines. Single frame pictures of the charts were taken with the Bolex camera equipped with the 26 mm. focal length lens, using Super X film. Exposures were made at each diaphragm opening (F1.9 to F22) in accordance with the recommendations of Reference 8. The film was developed without reversal. The number of lines resolved by the lens-film system was determined with the aid of a 12X magnifying glass and the constancy of spacing of the charts on certain of the nega-

TIVES WAS DETERMINED WITH THE MICROMETER ATTACHMENT ON THE BAUSCH AND LOMB MICROSCOPE.

OVEN CALIBRATION

THE AIR DEFLECTING VANES (SEE FIGURE 1) OF THE EXPERIMENTAL OVEN WERE ADJUSTED WITH THE AID OF THE VELOMETER TO GIVE OPTIMUM UNIFORMITY OF AIR FLOW ACROSS THE OVEN CAVITY AT APPROXIMATELY ROOM TEMPERATURE. THE BEST RESULTS WERE OBTAINED WITH THE OVEN BLOWER OPERATING AT THE HIGHEST OBTAINABLE SPEED (750 RPM). THE MAXIMUM AIR VELOCITY OF APPROXIMATELY 275 FT/MINUTE WAS MEASURED NEAR THE DOOR OF THE OVEN, DECREASING TO 50 FT/MINUTE NEAR THE REAR OVEN WALL. VARIATION FROM TOP TO BOTTOM OF THE OVEN WAS 275 TO 50 FT/MINUTE.

SEVERAL FINE WIRE THERMOCOUPLES WERE EMBEDDED IN THE CENTER PLANE OF 0.125" X 1" X 15" SPECIMENS OF PLEXIGLAS WHICH WERE THEN HUNG IN THE TENSILE GRIPS IN THE OVEN AND ORIENTED IN ACCORDANCE WITH THE PROPOSED TEST METHOD. THE SIGNAL FROM THESE AND SEVERAL OTHER THERMOCOUPLES IN THE AIR STREAM WAS RECORDED AS THE OVEN TEMPERATURE WAS INCREASED TO ONE OF SEVERAL CONSTANT TEMPERATURES. THESE RECORDS WERE ANALYSED FOR OVEN HEATING TIME AND UNIFORMITY OF TEMPERATURE.

THERMOMETER CALIBRATION

SEVERAL MERCURY THERMOMETERS WERE CALIBRATED, TOTALLY IMMERSED, WITH THE AID OF THE NBS CERTIFIED THERMOMETER.

AIR PRESSURE CALIBRATION

THE AIR PRESSURE GAGES (SEE FIGURE 5, PAGE 32) USED TO PRESET THE DESIRED CONSTANT PRESSURE TO THE FORMING EQUIPMENT WERE CALIBRATED AGAINST A PRECISION TYPE PRESSURE GAGE. THE PRESSURE INDICATORS AND THE PRESSURE RECORDER WERE CALIBRATED FOR BOTH THE 0 TO 10 PSIG. AND THE 0 TO 100" MERCURY RANGE IN ACCORDANCE WITH REFERENCES 12 AND 13.

OVEN MODIFICATION

AFTER COMPLETION OF THE TESTS TO OBTAIN THE MODULUS OF ELASTICITY OF THE PLASTICS AT HIGH TEMPERATURE, THE EXPERIMENTAL OVEN WAS REVISED BY ADDING THE AIR-CONTROL AND INDICATING SYSTEMS AND THE MOTION TRANSMITTING SYSTEM SHOWN IN FIGURES 2, 5 AND 7. THE TEMPERATURE RECORDING PEN WAS CALIBRATED EVERY 10°C. FROM 70 TO 160°C. AGAINST ONE OF THE CALIBRATED THERMOMETERS. THE MOTION TRANSMITTING SYSTEM AND RECORDING PEN WERE CALIBRATED AGAINST MEASURED MOVEMENTS OF THE MOTION TRANSMITTING CABLE (FIGURE 7).

SPECIMEN PREPARATION

Specimens were cut from the 1/8" and 1/4" thick plastic sheets to provide 1/8" or 1/4" x 1/2" x 5" sections for flexural deformation tests. The long edges of these pieces were milled smooth. Two sections of the 0.150" thick vinyl base plastic were stacked together to provide one test specimen.

Numerous 0.125" x 1" x 15" specimens of Plexiglas were prepared for the high temperature modulus of elasticity test by hand scraping the sawed edges. Gage marks were placed approximately 12" apart and perpendicular to the long axis on one surface of the specimen using an acrylic base white paint in a ruling pen (see Figure 2). Similar specimens of vinyl and acetate base plastics were prepared. Inasmuch as the allyl base plastic sheets were 12" x 12", it was necessary to use 0.125" x 1" x 12" specimens, but otherwise the procedure was the same.

Specimens of every available thickness of each of the plastic materials were cut to approximately 12" diameter discs or 11" squares and were identified by scribing near the edge. One 0.125" x 7" diameter and one 0.125" x 6" diameter disc were prepared from the allyl base plastic sheets.

Several 1-1/2" x 12" specimens of allyl plastic were prepared for all thicknesses of this material. The edges of these specimens were very carefully smoothed and beveled to eliminate minor edge fractures.

SECTION V

CONDUCT OF TEST

FLEXURAL DEFORMATION VS. TEMPERATURE

The measured width and thickness of the milled flexural deformation specimens were used to calculate the desired load to be used on the apparatus described in Reference 10. A curve of deflection vs. bath temperature was then obtained as the bath temperature was raised at a rate of 2°C./minute. Each specimen was tested with the 1/2" long axis parallel to the direction of load (the specimen rested on one long milled edge). Only one specimen was tested per stress.

SECTION VI

CONDUCT OF TEST

MODULUS OF ELASTICITY

THE THICKNESS OF EACH SPECIMEN WAS MEASURED ONCE AND THE WIDTH WAS MEASURED AT THREE LOCATIONS TO THE NEAREST 0.001", WITH A BENCH MICROMETER EQUIPPED WITH A 0 TO 1" FEDERAL DIAL GAGE. THE AVERAGE OF THE WIDTH MEASUREMENTS AND THE SINGLE THICKNESS MEASUREMENT WERE USED TO CALCULATE THE LOAD REQUIRED TO PRODUCE THE DESIRED STRESS. THE LOWER TENSILE GRIP, THE BOTTOM SUPPORTING DISC AND SUFFICIENT LEAD WEIGHTS WERE THEN WEIGHED TO PRODUCE THE REQUIRED LOAD. THE SUPPORTING DISC AND LEAD WEIGHTS WERE THEN PLACED IN PROPER SEQUENCE ON THE MOVABLE PLATFORM BELOW THE OVEN CAVITY FLOOR (FIGURE 2).

THE UPPER AND LOWER TENSILE GRIPS WERE PLACED ON EACH OF FIVE 1" X 15" SPECIMENS.

THREE CALIBRATED THERMOMETERS WERE HUNG IN THE OVEN IN THE PLANE OF THE SPECIMENS. THE EXPERIMENTAL OVEN WAS MAINTAINED AT A CONSTANT TEMPERATURE UNTIL EQUILIBRIUM CONDITIONS WERE ESTABLISHED.

THE BOLEX CAMERA, LOADED WITH MICROCOPY FILM, WAS PLACED ON THE TRIPOD, ALIGNED AND FOCUSSED ON THE PLANE OF THE SPECIMENS WITHIN THE OVEN. THE MIRROR AND TIMER WERE ADJUSTED SO THAT THE TIMER NUMERALS WOULD BE RECORDED ON THE NEGATIVE.

THE OVEN BLOWER WAS TURNED OFF, THE DOOR OPENED AND THE 5 SPECIMENS AND GRIPS WERE PLACED IN THE OVEN BY THREADING THE RODS ON EACH GRIP THROUGH THE PROPER HOLE IN THE FLOOR AND TOP OF THE OVEN. WING NUTS WERE SCREWED ON THE UPPER RODS TO SUPPORT THE SPECIMENS IN THE OVEN. THE OVEN DOOR WAS CLOSED IMMEDIATELY AND THE BLOWER STARTED.

THE ROD ON EACH LOWER TENSILE GRIP WAS COUPLED TO THE PROPER SUPPORTING DISC, TAKING CARE NOT TO STRETCH THE SPECIMEN IN THE OVEN. APPROXIMATELY 25 MINUTES AFTER THE OVEN REGAINED TEMPERATURE EQUILIBRIUM (OR 45 MINUTES FROM CLOSING THE DOOR) THE WING NUTS SUPPORTING THE SPECIMENS WERE CAREFULLY TIGHTENED ON TOP OF THE OVEN TO MAKE THE SPECIMEN TAUT WITHOUT STRETCHING. THE LIGHTS WITHIN THE OVEN WERE TURNED ON AND SEVERAL SINGLE FRAME PICTURES WERE MADE OF A PLACARD DESCRIBING THE TEST. THE PLACARD WAS REMOVED AND THE ORIGINAL LENGTH OF THE SPECIMENS WAS RECORDED ON THE FILM. THE STRING WAS PULLED TO COLLAPSE THE MOVABLE PLATFORM BELOW THE OVEN, THUS APPLYING THE LOADS AND SIMULTANEOUSLY STARTING THE TIMER. SINGLE FRAME PICTURES WERE MADE AT APPROPRIATE INTERVALS AS THE SPECIMENS ELONGATED.

AFTER THE NEGATIVE WAS DEVELOPED, THE IMAGE WAS PROJECTED THROUGH THE

16 MM. PROJECTOR AT A MAGNIFICATION OF 1 TO 1-1/2. THE PROJECTED LENGTH OF EACH SPECIMEN AT ZERO TIME WAS RECORDED. THE PROJECTED LENGTH AT PERIODIC INTERVALS AFTER LOADING WAS ALSO RECORDED. THE TIMER IN THE FIELD OF VIEW OF THE CAMERA PROVIDED AN ACCURATE TIME SCALE. THUS, THE STRAIN AT ANY TIME COULD BE CALCULATED BY DIVIDING THE CHANGE IN LENGTH BY THE ORIGINAL SPECIMEN LENGTH. FROM THIS CALCULATION THE MODULUS OF ELASTICITY AT TIME = 30 SECONDS WAS DETERMINED BY:

$$E_{30} = \frac{\text{Initial Stress}}{\text{Strain at 30 Seconds}} \, (1 + \text{strain at 30 seconds})$$

WHERE E_{30} = MODULUS OF ELASTICITY IN TENSION, 30 SECONDS AFTER LOAD APPLICATION.

INITIAL STRESS = STRESS BASED ON ORIGINAL CROSS SECTION

$$\text{Strain} = \frac{\text{Change in length of specimen at 30 seconds}}{\text{Original length}}$$

THE TERM IN THE PARENTHESIS IS INTENDED TO APPROXIMATELY CORRECT TO THE TRUE STRESS AT 30 SECONDS AND IS BASED ON THE ASSUMPTION THAT THE CROSS SECTION OF THE SPECIMEN DECREASES PROPORTIONALLY WITH THE INCREASE OF STRAIN. NO ATTEMPT WAS MADE TO INCLUDE POISSON'S RATIO IN THE CORRECTION.

THIS PROCEDURE WAS REPEATED AT SEVERAL TEMPERATURES FOR THE OTHER TYPES OF PLASTICS TO PROVIDE DATA FOR A MODULUS OF ELASTICITY VS. TEMPERATURE GRAPH. THIS GRAPH WAS USED AS A BASIS FOR CHOOSING THE OVEN TEMPERATURE FOR THE FORMING TESTS.

SECTION VII

CONDUCT OF TEST

SPHERICALLY BLOW FORMING

PLEXIGLAS II OF A NOMINAL THICKNESS OF 1/8" WAS USED DURING THE INITIAL TESTS OF THE BLOW FORMING JIG. THE OVEN WAS MAINTAINED AT A CONSTANT TEMPERATURE OF 135°C. (275°F.) UNTIL THE JIG IN THE OVEN, AS WELL AS THE OVEN ITSELF WERE IN EQUILIBRIUM. THE OVEN BLOWER WAS STOPPED, THE DOOR OPENED AND TWO OF THE "C" CLAMPS HINGED TO THE TOP RING OF THE FIXTURE WERE RAISED. THE FRONT SPRING WAS TEMPORARILY REMOVED (SEE FIGURE 7). THE SPECIMEN WAS THEN CLIPPED TO THE FLANGE ON THE PERIPHERY OF THE TOP RING WITH THE AID OF 4 SPRING-LOADED PAPER CLAMPS. THE "C" CLAMPS WERE LOWERED, THE FIXTURE WAS CENTERED UNDER THE MOTION TRANSMITTING CABLE, THE DOOR WAS CLOSED AND THE OVEN BLOWER STARTED.

The time of insertion of the 1/8" thick specimen in the oven was noted on the chart of the three-pen recorder. When necessary, the Conoflow pressure regulator was preset with the aid of one of the pressure gages shown in Figure 5) without delivering air to the forming fixture by temporarily connecting together the inlet and outlet lines to the fixture. After 15 minutes of heating, the specimen had sagged to the bottom plate. The air clamps were turned on and the zero adjustment was made in the motion transmitting cable so that the motion recording pen indicated zero as the cable weight rested on the top center of the specimen.

The switch was turned on to start the recorder and to open the solenoid valve to deliver air from the accumulator and supply line to the space below the test specimen. The separate air line between this space and the pressure indicator and recorder transmitted the pressure increase in the jig to these instruments. Thus, a record of air pressure used to blow the dome, oven temperature and the deflection of the apex of the dome were recorded vs. time. Occasionally, minor adjustments in the air pressure were necessary during the first minute of the forming operation.

Numerous similar tests were made with Plexiglas II to establish the constant air pressure required to produce a deflection of approximately 4" of the apex of a test specimen of a thickness of 0.110" (the minimum permitted for nominal 0.125" thick Plexiglas II by Reference 3). To test the validity of the results, specimens of commercially available material of thicknesses other than those permitted by Reference 3 were tested. These tests also served to establish the reproducibility of test results and to provide data on the effect of prolonged (30-45 minutes) heating on the deflection of the dome.

Similar tests at 135°C. (275°F.) with appropriate preheating times were made of 0.060", 0.250", 0.500" thick Plexiglas II, all pertinent thicknesses of Plexiglas I-A and of the 0.250" thick Lucite. Unfortunately, material of sufficiently different thickness was not available to permit an exhaustive study of the 0.500" thick Plexiglas in a manner similar to that described for 0.125" thick material.

In general, the test specimens were permitted to return to the flat state after the record was obtained. In some few cases, the forming fixture was removed from the oven, connected to the air lines with rubber hoses and the dome reblown and cooled as exhibits.

Vinylite conforming to Reference 5 was similarly tested at 135°C. (275°F.). The surface of the specimen became roughened as if it were unmolding and the oven temperature was lowered to 86°C. (187°F.). Tests were conducted on the 0.060", 0.125" and 0.150" thick material to determine the air pressures re-

QUIRED TO PRODUCE APPROXIMATELY A 4" DEFLECTION.

SIMILAR TESTS AT 135°C. (275°F.) WERE MADE WITH THE 0.125" AND 0.250" THICK ACETATE SHEETS. WHITENING AND CRACKING OF THESE MATERIALS WERE OBSERVED AND THE TEST TEMPERATURE WAS CHANGED TO 114°C. (237°F.). AT THAT TEMPERATURE, SPHERICAL FORMING TESTS WERE CONDUCTED ON THE 0.060", 0.125" AND 0.250" THICK SHEETING TO DETERMINE THE AIR PRESSURES REQUIRED TO PRODUCE CLEAR, SPHERICAL SECTIONS OF MAXIMUM HEIGHT. THE POSSIBLE HEIGHT WAS LIMITED BY THE TENDENCY OF THE MATERIAL TO WHITEN.

DURING ATTEMPTS TO MAKE MODULUS OF ELASTICITY TESTS, IT WAS DETERMINED THAT THE ALLYL BASE RESIN COULD NOT BE HEATED AND GRIPPED WITHOUT FRACTURING. CONSEQUENTLY AN ATTEMPT WAS MADE TO "BLOW-FORM" THE MATERIAL WHILE ENCLOSED IN PROTECTIVE RUBBER SHEETS. A 0.125" X 7" DIAMETER DISC OF THIS MATERIAL WAS HEATED FOR 15 MINUTES AT 135°C. (275°F.) IN THE EXPERIMENTAL OVEN TOGETHER WITH A THIN 10" X 20" RUBBER SHEET. THE OVEN DOOR WAS THEN OPENED AND THE DISC QUICKLY COVERED ON BOTH SIDES WITH THE RUBBER SHEET. THIS SANDWICH WAS CENTERED IN THE FORMING FIXTURE SO THAT THE CLAMPING RING WOULD ENGAGE THE DOUBLED RUBBER ONLY. AN ADDITIONAL HEATING PERIOD OF 20 MINUTES WAS USED. THE CLAMPING RING WAS LOWERED AND THE FORMING AIR AND RECORDER TURNED ON. CONTINUOUS OBSERVATION OF THE SPECIMEN AND MANUAL ADJUSTMENT OF THE AIR PRESSURE WAS MAINTAINED. THE PRESSURE WAS INCREASED SLOWLY FROM ZERO UNTIL A SUDDEN MOVEMENT OF THE SANDWICH AND A SHARP CHANGE IN MOTION RECORD INDICATED FRACTURE OF THE ALLYL HAD OCCURRED. THE 0.125" X 6" DIAMETER DISC WAS SIMILARLY TREATED EXCEPT THAT THE AIR PRESSURE WAS RAISED MORE SLOWLY FROM ZERO. THE TOTAL TIME TO ATTAIN A PRESSURE OF 0.5 PSI. WAS 5 MINUTES.

SECTION VIII

CONDUCT OF TEST

CYLINDRICAL FORMING

SEVERAL 0.125" X 1-1/2" X 12" SPECIMENS OF THE ALLYL BASE PLASTIC WERE HEATED TO 130°C. (266°F.) FOR 15 MINUTES, REMOVED FROM THE OVEN TO A FLOCKED-RUBBER COVERED CYLINDER OF 3.1" RADIUS OF CURVATURE AND ATTEMPTS WERE MADE TO SLOWLY MANUALLY BEND THESE BEAMS OVER THE FORM.

A FORM, MADE OF TWO HALF DISCS OF PLYWOOD CUT TO A RADIUS OF 3.1" AND PARTIALLY COVERED WITH A 6" WIDE STRIP OF THIN STEEL, WAS PLACED IN THE OVEN AT 130°C. (266°F.) WITH THE FLAT, OPEN SIDE UP. AFTER EQUILIBRIUM WAS ESTABLISHED ONE OF THE 0.125" THICK SPECIMENS OF ALLYL BASE PLASTIC WAS PLACED IN THIS FEMALE FORM AND LIGHTLY AND UNIFORMLY LOADED WITH A HEATED SANDBAG.

OBSERVATION OF THE DEFORMATION OF THE BEAM WAS MAINTAINED.

SIMILAR 0.250" AND 0.500" THICK SPECIMENS WERE HEATED FOR APPROPRIATE TIMES AT 177°C. (350°F.), REMOVED FROM THE OVEN AND BENT OVER FLOCKED-RUBBER COVERED FORMS OF APPROPRIATE RADIUS.

THE OVEN TEMPERATURE WAS THEN REDUCED TO 95°C. (203°F.), SEVERAL OF THE 0.125" THICK SPECIMENS OF THIS PLASTIC WERE HEATED 15 MINUTES, REMOVED AND SLOWLY MANUALLY FORMED OVER A CYLINDER OF 3.1" RADIUS. SIMILARLY, 0.060", 0.250" AND 0.500" THICK BEAMS WERE FORMED OVER CYLINDERS OF 1.5", 6.3" AND 12.5" RADII, RESPECTIVELY. THE RADII OF CURVATURE OF THE RESPECTIVE FORMS WERE CALCULATED TO PRODUCE 2% STRAIN AT THE SURFACE OF EACH OF THE BEAMS.

SECTION IX

CONDUCT OF TEST

OPTICAL HAZE MEASUREMENTS

LUMINOUS TRANSMITTANCE AND HAZE MEASUREMENTS (SEE REFERENCE 1) WERE MADE AT THE APEX OF ONE SPHERICAL SECTION FORMED FROM EACH PRESCRIBED ORIGINAL THICKNESS OF ALL PLASTIC MATERIALS AND ON THE PARTIAL CYLINDERS OF THE FOUR THICKNESSES OF ALLYL BASE PLASTIC. SIMILAR MEASUREMENTS WERE MADE OF THE FLAT SHEET STOCK OF EACH MATERIAL.

SECTION X

RESULTS

FIGURES 8 TO 16, INCLUSIVE (PAGES 35 TO 43), SHOW THE FLEXURAL DEFORMATION VS. TEMPERATURE AT VARIOUS APPLIED STRESSES FOR COMPOSITE (TWO 1/8" X 1/2" X 5") AND SOLID (1/4" X 1/2" X 5") SPECIMENS OF THE VARIOUS PLASTIC MATERIALS. THE TESTS WERE MADE IN ACCORDANCE WITH REFERENCE 10 EXCEPT AS NOTED ON THE GRAPHS. INASMUCH AS THE TEMPERATURE AT WHICH A FLEXURAL DEFORMATION OF 10 MILS OCCURS IS DEFINED AS THE HEAT DISTORTION TEMPERATURE (REFERENCE 10), THIS TEMPERATURE WAS PLOTTED AGAINST THE APPLIED STRESS IN FIGURE 17, PAGE 44.

FIGURE 18 SHOWS THE MODULUS OF ELASTICITY IN TENSION OF 0.125" THICK PLASTIC SPECIMENS AT CONSTANT TEMPERATURE THIRTY SECONDS AFTER A LOAD WAS APPLIED. APPRECIABLE ELONGATION (APPROXIMATELY 10%) OF THE CELLULOSE ACETATE (LUMARITH) WAS NOTED PRIOR TO STRETCHING, APPARENTLY DUE TO THE WEIGHT OF THE SPECIMEN ITSELF.

The thirty second modulus of elasticity of the Homalite CR-39 (allyl base plastic, AF12040) could not be determined. The specimens tore at the clamps as the load was applied.

Figures 19 to 26, inclusive, show the apex height attained by acrylic specimens when blown into spherical sections through an 8" diameter ring by constant air pressure at 135°C. (275°F.) forming temperature. The deflections noted on the graphs were taken from the recorded deflections at an arbitrary elapsed time of three minutes after the application of the air pressure. At this time, the time rate of change of deflection had become approximately constant. A rapid time rate of change of deflection of the acrylic specimens was noted when the deflection at 3 minutes was approximately 100% of a hemisphere or 4". Apparently the greater creep rate of this material at high deflections is due to the high stresses produced by thinning at the apex.

The effect on 1/8" thick Plexiglas I-A of slowly increasing the internal pressure is shown on Figure 34.

When similarly tested, the few specimens of Lucite HC202 and HC212 (Figure 23,) deformed to the same extent as Plexiglas II.

Figures 27 and 28, page 50, show the test results on spherical sections formed from the available thicknesses of Vinylite at a constant temperature of 86°C. (187°F.) and constant pressure.

Figures 29 to 32, inclusive, show the results of similar tests on the acetate base sheets. Lumarith was observed to become white or frosty during forming. This defect started at the apex, but spread over the surface with a tendency toward parallel striations. Plastacele was observed to fissure or crack, generally in parallel lines. To reduce whitening of the Lumarith or tearing of the Plastacele, it was necessary to limit the maximum heights of the domes to approximately 60 to 70% of a hemispherical section. Even when the oven was maintained at a temperature of 114°C. (237°F.), it was evident, by the odor, that the plasticizer was being driven from the test specimens. In the case of Lumarith the odor was very strong. The effect of heating time is shown on Figure 33, page 53.

The forming tests on acetate sheets at 135°C. (275°F.), and at 114°C. (237°F.) do not correlate with the modulus of elasticity measurements. The air pressures required to form hemispheres at these temperatures do not approximate those to be expected from the modulus measurements or the results obtained from the acrylic and vinyl specimens. It was observed that increasing the deforming air pressure did not produce a corresponding increase of

DEFLECTION ALTHOUGH THE MATERIAL WAS BLOWN TO A HEMISPHERE AND HELD AT A CONSTANT TEMPERATURE. IT APPEARS THAT THIS MATERIAL REACHES A LIMIT OF EXTENSIBILITY AT APPROXIMATELY THE HEMISPHERICAL SHAPE. THE RESULTS OF INCREASING THE FORMING AIR PRESSURE ON A 0.135" THICK ACETATE SHEET ARE SHOWN ON FIGURE 34.

IT WAS OBSERVED THAT THE ACRYLIC AND VINYL SPECIMENS WOULD RETURN APPROXIMATELY TO THE FLAT SHEET STATE WHEN THE DEFORMING AIR PRESSURE WAS REMOVED. HOWEVER, REDUCING THE AIR PRESSURE TO ZERO UNDER ACETATE DOMES PRODUCED LITTLE CHANGE OF HEIGHT. THIS MATERIAL APPARENTLY HAS LITTLE ELASTIC MEMORY OR TENDENCY TO FLATTEN.

THE RELATION BETWEEN FORMING PRESSURE AND ORIGINAL THICKNESS OF THE SPHERICALLY FORMED ACRYLIC AND VINYL SPECIMENS IS SHOWN IN FIGURE 35.

THIS GRAPH WAS MADE BY PLOTTING THE PRESSURES USED DURING FORMING EACH MATERIAL VS. NOMINAL THICKNESS. THUS, THIS GRAPH SHOWS THE PRESSURE REQUIRED TO PRODUCE APPROXIMATELY 8" DIAMETER HEMISPHERES AT THE INDICATED TEMPERATURES, THREE MINUTES AFTER APPLICATION OF PRESSURE, FOR VARIOUS THICKNESSES OF PLASTIC SHEET.

DURING THE ATTEMPT TO SPHERICALLY FORM THE 0.125" x 7" DIAMETER DISC OF HOMALITE CR-39 IN THE RUBBER BLANKET, THE DEFLECTION WAS NEGLIGIBLE UNTIL FRACTURE. THE RUBBER BLANKET SURROUNDING THE 0.125" x 6" DIAMETER DISC OF HOMALITE CR-39 DEFLECTED APPROXIMATELY 3/8" BY STRETCHING BETWEEN THE EDGE OF THE DISC AND THE CLAMPING RING OF THE SPHERICAL FORMING FIXTURE. THE PLASTIC DISC ITSELF APPEARED TO HAVE DEFORMED INTO A SPHERICAL SECTION OF APPROXIMATELY 0.1" HEIGHT PRIOR TO FRACTURE.

THE 0.125" x 1-1/2" x 12" BEAMS OF HOMALITE CR-39 HEATED TO 130°C. (266°F.) BROKE DURING MANUAL FORMING OVER THE MALE CYLINDRICAL FORM OF 3.1" RADIUS AND WHEN UNIFORMLY LOADED IN A FEMALE CYLINDRICAL FORM OF THE SAME RADIUS.

THE THERMALLY INDUCED STRESSES IN THE 0.250" AND 0.500" THICK HOMALITE BEAMS DURING HEATING TO OR COOLING FROM 177°C. (350°F.) WERE SUFFICIENT TO PRODUCE FRACTURE OF THE MATERIAL WITHOUT APPLICATION OF EXTERNAL LOAD.

AFTER HEATING 0.060", 0.125", 0.250" AND 0.500" THICK HOMALITE CR-39 BEAMS AT 95°C. (203°F.) IT WAS POSSIBLE TO REMOVE THE MATERIAL FROM THE PREHEATING OVEN AND FORM PARTIAL CYLINDERS OVER THE RESPECTIVE 1.5", 3.1", 6.3" AND 12.5" RADIUS CYLINDRICAL FORMS. THE SUCCESS OF THIS FORMING OPERATION APPEARS TO BE DEPENDENT ON THE SMOOTHNESS OF THE SURFACE AND EDGE FINISH OF THE BEAM AND ON AN EXTREMELY SLOW APPLICATION OF DEFORMING LOAD. VISUAL OBSERVATION OF THE COOLED, CYLINDRICALLY FORMED ALLYL SPECIMENS SHOWED THAT LITTLE OR NO DISTORTION OR HAZE RESULTED FROM THE FORMING OPERATION.

THE RESULTS [illegible]

ENCE 11) FOR ALL [illegible]

[illegible]

LUMINOUS TRANSMITTANCE AND HAZE OF PLASTIC SPECIMENS

(MEASUREMENTS MADE IN ACCORDANCE WITH
A.S.T.M. METHOD D672-45T)

SPECIMEN TYPE	AVERAGE CENTER THICKNESS OF MATERIAL PRIOR TO FORMING (INCHES)	TRANSMITTANCE TOTAL (%)	TRANSMITTANCE PARALLEL (%)	HAZE (%)
PLEXIGLAS I-A DOMES	0.062	93	92	2
	.120	93	91	2
	.245	93	91	2
	.505	93	91	2
PLEXIGLAS II DOMES	0.057	93	91	2
	.116	93	90	3
	.246	93	91	2
	.451	93	91	3
VINYLITE DOMES	0.061	87	84	3
	.135	80	77	4
	.156	78	76	3
ACETATE DOMES	0.061	90	85	6
	.126	87	82	6
	.250	88	78	11
HOMALITE CYLINDERS	0.125	93	92	2
	.245	93	91	2
	.508	92	90	2
PLEXIGLAS FLAT SHEET	0.503	92	90	2
VINYLITE FLAT SHEET	.154	74	71	4
ACETATE FLAT SHEET	.244	87	80	8
HOMALITE FLAT SHEET	.483	91	89	2

SECTION XI

DISCUSSION OF RESULTS

HEAT DISTORTION TEMPERATURE METHOD

THE MAXIMUM PROBABLE ERROR OF THE HEAT DISTORTION TEMPERATURE MEASUREMENTS IS OF THE ORDER OF $\pm 3^{\circ}$C. (5°F.).

MODULUS OF ELASTICITY METHOD

MEASUREMENTS MADE WITH THE MICROMETER EYEPIECE OF THE MICROSCOPE OF THE LENS RESOLUTION CHART IMAGES ON THE 16 MM. NEGATIVES SHOW THAT ANY LINEAR DISTORTION OF THE LENS-FILM-DEVELOPING SYSTEM IS LESS THAN THE PROBABLE ERROR OF LOCATING THE CHARTS PRIOR TO PHOTOGRAPHING.

THE ERROR OF MEASURING THE CHANGE OF LENGTH OF THE PROJECTED IMAGE OF THE MODULUS OF ELASTICITY SPECIMENS IS APPROXIMATELY ±2%. THUS, THE CALCULATED STRAIN MAY BE IN ERROR BY THIS AMOUNT. THE LOWER CLAMPS, SUPPORT RODS AND ADDITIONAL STRESSING WEIGHTS WERE MEASURED TO WITHIN ±0.01 POUND AND THE WIDTH AND THICKNESS OF THE SPECIMENS TO ±0.001", THEREFORE, THE INITIAL STRESS ON THE MODULUS OF ELASTICITY SPECIMENS MAY BE IN ERROR BY ±2%. AS A CONSEQUENCE OF THESE ERRORS THE CALCULATED MODULUS OF ELASTICITY MAY BE IN ERROR BY ±4%.

SEVERAL TESTS WITH THERMOMETERS AND THE RECORDING POTENTIOMETER SHOWED THAT THE TEMPERATURE OF THE AIR IN THE VERTICAL CENTER PLANE OF THE OVEN PARALLEL TO THE AIR STREAM DROPPED ONLY 2°C. (4°F.) FROM INLET TO OUTLET OF THE OVEN CAVITY AND THAT ANY POINT WITHIN THIS PLANE WAS AT CONSTANT TEMPERATURE WITHIN ±1°C. (2°F). IT WAS ALSO DETERMINED THAT THE RECORDED TEMPERATURE OF THE OVEN CAVITY WAS WITHIN 0.5°C. (1°F.) OF THE AIR TEMPERATURE AT THE CENTER OF THE OVEN. INASMUCH AS CALIBRATED THERMOMETERS WERE HUNG NEAR THE MODULUS OF ELASTICITY SPECIMENS DURING THE TESTS, THE TEMPERATURE OF ANY SPECIMEN WAS KNOWN TO BE WITHIN ±1°C. (2°F.).

SPHERICALLY FORMING METHOD

TESTS SHOWED THAT THE RECORDED AIR PRESSURE WAS WITHIN ±5% OF THAT OF A PRECISION TYPE GAGE INSERTED IN THE FORMING AIR LINE, PROVIDED THE LINE WAS SEALED AGAINST LEAKS. IN PRACTICE LEAKAGE SOMETIMES OCCURRED AROUND THE PLASTIC SPECIMEN WHILE BEING FORMED, BUT THERE WAS NO FLOW OF AIR IN THE INDEPENDENT LINE FROM THE ENTRAPPED AIR SPACE TO THE RECORDER. THEREFORE, THE RECORD WAS NOT INFLUENCED BY LEAKAGE AT THE DOME. OBSERVATION OF THE GAGES AND THE PRESSURE RECORD SHOW THAT THE CONOFLOW REGULATOR COMBINED WITH FREQUENT MANUAL ADJUSTMENT HELD THE FORMING AIR PRESSURE TO WITHIN ±0.1 PSI. AND ±0.5 PSI. OF THE DESIRED VALUE FOR THE 0 TO 10 PSI. AND 0 TO 52.5 PSI. RANGES, RESPECTIVELY.

CALIBRATION OF THE MOTION SENSING ASSEMBLY SHOWED THAT THE PEN RECORDED THE MOTION OF THE TRANSMITTING CABLE AND WEIGHT TO ±1% OF THE 4" MAXIMUM HEMISPHERICAL DOME HEIGHT. THE ZERO HEIGHT OF THE CABLE WAS SET PRIOR TO EACH TEST TO WITHIN ±0.04".

THE REPRODUCIBILITY OF THE MODULUS OF ELASTICITY TEST RESULTS ON ACRYLIC SPECIMENS IS ±50% AT THE LOWEST TEST TEMPERATURE DUE PRIMARILY TO THE RAPID CHANGE OF MODULUS WITH MATERIAL TEMPERATURE. THE REPRODUCIBILITY OF THE RESULTS IS BEST (APPROXIMATELY ±5%) AT INTERMEDIATE TEMPERATURES. AT THE HIGHER TEST TEMPERATURES THE REPRODUCIBILITY BECOMES APPROXIMATELY ±20%. IN THE CASE OF PLEXIGLAS II SOME OF THIS SCATTER MAY BE DUE TO THE TEST SPECIMENS BEING TAKEN FROM SHEETS MADE AT TWO DIFFERENT PRODUCTION UNITS, NAMELY THE BRISTOL, PENNA., AND KNOXVILLE, TENN., PLANTS OF THE ROHM & HAAS COMPANY.

THE REPRODUCIBILITY OF RESULTS OF SPHERICALLY FORMING ACRYLIC SHEETS WAS FOUND TO BE APPROXIMATELY ±5% OF THE HEMISPHERICAL HEIGHT OF 4" FOR THE SAME TEMPERATURE, PRESSURE AND THICKNESS OF SPECIMEN. A LACK OF REPRODUCIBILITY WAS NOTED IF THE SAME SHEET WAS FLATTENED WITHOUT COOLING, AND REBLOWN. THE SECOND DOME WAS HIGHER THAN THE FIRST. CONSEQUENTLY, NO DATA WERE TAKEN ON SUCH REBLOWING.

THE REPRODUCIBILITY OF RESULTS OF SPHERICALLY FORMING VINYLITE OF SIMILAR THICKNESS WAS NOT AS SATISFACTORY. THE VARIATION OF HEIGHT WAS FOUND TO BE ±8% OF THE HEMISPHERICAL HEIGHT OF 4".

THE RESULTS OBTAINED IN SPHERICALLY FORMING CELLULOSE ACETATE SHEETING AT 114°C. (237°F.) WERE RANDOM. NOT ONLY DID HEATING TIME PRIOR TO FORMING SIGNIFICANTLY AFFECT THE HEIGHT OF THE SECTION (SEE FIGURE 33,) BUT PRESSURES DIFFERING BY A FACTOR OF 3 TO 4 PRODUCED DOMES OF APPROXIMATELY THE SAME HEIGHT FROM SHEETS OF APPROXIMATELY THE SAME THICKNESS (SEE FIGURES 29 AND 32. IT WAS FOUND THAT A PRESSURE OF 5 PSI. WOULD FORM A 60% HEMISPHERE OF 0.132" THICK LUMARITH WHEREAS A PRESSURE OF 3/4 PSI. WOULD FORM A 50% HEMISPHERE OF 0.130" THICK PLASTACELE (SEE FIGURES 29 AND 30) THIS DIFFERENCE IS BELIEVED TO BE DUE TO A DIFFERENCE IN THE HIGH TEMPERATURE ELONGATION CHARACTERISTICS OF THE TWO MATERIALS CAUSED BY A DIFFERENCE IN COMPOSITION OR OF THE METHOD OF MANUFACTURE. IT WAS NOTED THAT THESE MATERIALS HAD A DIFFERENCE IN HEAT DISTORTION TEMPERATURE.

THE ORIGINAL FORMING TEMPERATURE OF 130°C. (266°F.) FOR ALLYL BASE PLASTICS WAS USED AFTER VERBAL CONVERSATIONS WITH TWO MANUFACTURERS OF THIS MATERIAL. BECAUSE OF THE FAILURE OF GENTLY, UNIFORMLY LOADED DISCS OF THE MATERIAL TO SPHERICALLY FORM AND THE ADVICE OF ONE OF THESE MANUFACTURERS THAT THE MATERIAL IS NOT FORMABLE, FURTHER EXPERIMENTS WITH SPHERICALLY FORMED SHAPES WERE DISCONTINUED. THE DISINTEGRATION OF SEVERAL OF THE UNSTRESSED ALLYL BEAMS HEATED TO 177°C. (350°F.) FROM THERMAL STRESSES AND THE RUPTURE OF BEAMS AT 130°C. (266°F.) SUGGESTED LOWERING THE PREHEATING TEMPERATURE TO 95°C. (203°F.).

CONCLUSIONS

1. The flexural deformation vs. temperature and the Heat Distortion Temperature (at a deflection of 10 mils, Reference 10) of the subject plastic specimens is a function of the applied stress, thickness of original material and of the type of polymer (see Figures 8 to 16, inclusive.) It should be noted that there appears to be a correlation between Heat Distortion Temperature of the several materials and the modulus of elasticity (30 seconds) in tension of 150°C. (302°F.). (Compare Figure 17 with Figure 18). However, there is no correlation between Heat Distortion Temperature and pressure required to form a hemisphere at the test temperatures used.

The rate of change of flexural deformation with temperature at a constant stress is greater for Vinylite (see Figure 10) than for any of the other plastic materials tested. The rate of change of Heat Distortion Temperature with applied stress is less for Vinylite than for any of the other material tested (see Figure 17). The rate of change of Heat Distortion Temperature with low applied stress is greater for Homalite CR-39 than for any other material tested.

2. Both Plexiglas I-A and Plexiglas II change moduli of elasticity (at 30 seconds) in tension at a rapid rate with temperature within a narrow temperature range (see Figure 18). As the temperature of the acrylic materials is raised, the modulus reduces rapidly to an approximate minimum. Thereafter, increasing temperature produces relatively little reduction of modulus. Vinylite and Lumarith change moduli more uniformly with temperature. The data show that forming of Plexiglas I-A and Plexiglas II should be completed at temperatures above 110°C. (230°F.) and 135°C. (275°F.), respectively, to keep residual stresses in formed parts at a minimum. Only minor reductions of residual stresses in formed parts may be obtained by increasing these respective minimum temperatures.

The measurements of the modulus of elasticity of the acetate specimens are least accurate. The specimens stretched appreciably of their own weight during heating and prior to loading.

Figure 18 indicates an advantage to heating Vinylite and acetate sheets to high temperatures prior to forming in order to reduce the residual stresses in formed parts. However, when these materials are heated to 135°C. (275°F.), the Vinylite surface becomes rough and the acetate sheets lose plasticizer. Therefore, lower temperatures must be used.

3. There is a linear relation between the log of center deflection of 8" diameter spherical sections blown at constant temperature and pressure and the initial average center thickness of Vinylite and both types of acrylic sheets (see Figures 19 to 28). The limited data obtained for Lucite HC202 and HC212 show no difference between these materials and Plexiglas II (see Figure 23).

The rate of change of the log of deflection of the spherical sections decreases with large changes in original sheet thickness and the necessary changes of forming pressure (compare Figure 19 with 25,

4. There is a linear relationship between the constant pressure used to form approximately 8" diameter hemispheres at constant temperature and thickness of Vinylite and both types of acrylic sheet (see Figure 35, page 55).

5. Excessive heating times lower the center deflection obtained on 8" diameter spherical sections of Lumarith blown at constant temperature and pressure (see Figure 33). A similar effect was noted with Plastacele sheets.

6. There is no correlation between the center deflection of 8" diameter spherical sections formed of acetate sheet at constant temperature and the forming pressure (see Figures 29 to 32). Domes of similar height were formed from 0.132" and 0.135" thick Lumarith at 5 and 17 psi.

It should be noted that the 1/8" thick Plastacele sheets were deformable at lower pressures than the 1/8" thick Lumarith sheets.

7. There is a similarity between the formability characteristics of Vinylite and both types of acrylic sheets (see Figure 34). Increasing pressures produce a large increase of deflection of 8" diameter spherical sections formed at constant temperature.

Conversely, the formability characteristics of acetate sheets are quite different from those of acrylic. Increasing pressures produce a small increase of deflection of the spherical sections. There appears to be a maximum height to which the acetate domes may be blown (see Figure 34).

8. There is an elastic memory (ability to return to the flat state upon reheating a formed sheet) of Vinylite and both types of acrylic sheet. Domes formed from all three materials returned to the approximtely flat state when the forming air pressure was released and the materials were maintained at an elevated temperature.

Domes formed of acetate retracted very little when the air pressure was

REMOVED AND THE MATERIAL WAS MAINTAINED AT AN ELEVATED TEMPERATURE.

9. THERE IS A FUNDAMENTAL DIFFERENCE IN THE BEHAVIOR OF ACETATE SHEET SUBJECTED TO HIGH TEMPERATURE AND STRETCHING FORCES AND SIMILARLY TREATED VINYLITE AND ACRYLIC SHEET. THE FAILURE OF THE FORMER MATERIAL TO STRETCH SIGNIFICANTLY WITH LARGE INCREASES OF FORMING PRESSURE AS WELL AS THE LOW ELASTIC MEMORY ILLUSTRATE THIS DIFFERENCE.

10. HOMALITE CR-39 SHEETS CANNOT BE SPHERICALLY FORMED. THIS MATERIAL CAN BE CYLINDRICALLY FORMED TO 2% OUTER FIBER STRAIN PROVIDED CARE IS EXERCISED TO APPLY THE DEFORMING LOAD SLOWLY AND THE INTERNAL STRESSES PRODUCED BY DIFFERENTIAL COOLING ARE KEPT AT A MINIMUM.

11. IT IS POSSIBLE TO DIFFERENTIATE BETWEEN THE FORMABILITY CHARACTERISTICS OF THE FIVE SUBJECT PLASTIC SHEET MATERIALS WHEN THE MATERIALS ARE HEATED TO CONSTANT TEMPERATURES AND FORMED INTO 8" DIAMETER SPHERICAL SECTIONS BY APPLYING CONSTANT AIR PRESSURES.

A. HOMALITE CR-39 SHEET (SPECIFICATION AF12040) CANNOT BE SIGNIFICANTLY SPHERICALLY FORMED WITHOUT RUPTURE, IRRESPECTIVE OF TEMPERATURE AND PRESSURE.

B. THE CENTER DEFLECTION OF 8" DIAMETER SPHERICAL SECTIONS OF CELLULOSE ACETATE SHEETS (SPECIFICATION MIL-P-6887) WILL BE BETWEEN 50 AND 100% OF A HEMISPHERE WHEN THE MATERIAL IS HEATED TO 114°C. (237°F.) AND SUBJECTED TO A CONSTANT AIR PRESSURE OF 5 PSI. THE DEFLECTION MUST BE MEASURED 3 MINUTES AFTER THE PRESSURE IS APPLIED, FORMING MUST START AS THE PLASTIC ATTAINS EQUILIBRIUM TEMPERATURE CONDITIONS, THE SPECIMEN MUST BE TESTED ONLY ONCE AND THE HEIGHT OF THE DOME WILL NOT BE RELATED TO ORIGINAL SHEET THICKNESS. THE FORMED SHEETS WILL NOT RETURN TO THE ORIGINAL PLANE STATE IF THE AIR PRESSURE IS RELEASED AND THE TEMPERATURE IS MAINTAINED AT 114°C. (237°F.).

C. THE CENTER DEFLECTION OF 8" DIAMETER SPHERICAL SECTIONS OF VINYLITE (SPECIFICATION AF12041) FORMED AT A CONSTANT TEMPERATURE OF 86°C. (187°F.) WILL BE IN ACCORDANCE WITH THE FOLLOWING TABLE.

NOMINAL THICKNESS (INCHES)	CONSTANT AIR PRESSURE (PSI.)	CENTER DEFLECTION (% OF HEMISPHERE)
0.060	2.0	60 TO 100
.125	4.5	60 TO 100
.150	4.5	50 TO 100

THE CENTER DEFLECTION OF THE DOMES MUST BE MEASURED 3 MINUTES AFTER THE PRESSURE IS APPLIED, A SPECIMEN MUST BE TESTED ONLY ONCE AND FORMING MUST BE STARTED SHORTLY AFTER EQUILIBRIUM TEMPERATURE CONDITIONS ARE ESTABLISHED.

D. The center deflection of 8" diameter spherical sections of Plexiglas I-A (Specification MIL-P-6886, thickness tolerances of Table I) formed at a constant temperature of 135°C. (275°F.) will be in accordance with the following table.

Nominal Thickness (Inches)	Constant Air Pressure (Psi.)	Center Deflection (% of Hemisphere)
0.060	1.75	50 to 100
.125	3.75	50 to 100
.250	7.5	50 to 100
.500	15.2	50 to 100

The center deflection of the domes must be measured 3 minutes after the pressure is applied, a specimen must be tested only once and forming must be started shortly after equilibrium temperature conditions are established.

E. The center deflection of 8" diameter spherical sections of Plexiglas II (Specification MIL-P-5425, thickness tolerances of Table I) formed at a constant temperature of 135°C. (275°F.) will be in accordance with the following table.

Nominal Thickness (Inches)	Constant Air Pressure (Psi.)	Center Deflection (% of Hemisphere)
0.060	2.75	50 to 110
.125	6.75	60 to 110
.250	13.5	50 to 100
.500	27	70 to 120

The center deflection of the domes must be measured 3 minutes after the pressure is applied, a specimen must be tested only once and forming must be started shortly after equilibrium temperature conditions are established.

12. Simplified equipment similar to the spherical forming fixture and cylindrical forms described herein can be used for qualification testing of the formability characteristics of the subject plastic materials. The test method described herein will produce optically satisfactory specimens (see Table II) will indicate certain limitations of the formability of the materials and will differentiate between the formability characteristics of these materials.

BIBLIOGRAPHY

1. Contract P.O. AF-33(038)-22945 dated 26 June 1951 from Air Materiel Command, Wright-Patterson Air Force Base, Dayton, Ohio.

2. Specification MIL-P-6886; Plastic; Acrylic Sheet. Air Materiel Command, Wright-Patterson Air Force Base, Dayton, Ohio.

3. Specification MIL-P-5425; Plastic: Acrylic Sheet, Heat Resistant. Air Materiel Command, Wright-Patterson Air Force Base, Dayton, Ohio.

4. Specification MIL-P-6887; Plastic: Cellulose Acetate Base Sheet. Air Materiel Command, Wright-Patterson Air Force Base, Dayton, Ohio.

5. Specification AF12041; Plastic Sheet: Transparent, Vinyl Copolymer Base. Air Materiel Command, Wright-Patterson Air Force Base, Dayton, Ohio.

6. Specification AF12040; Plastic Sheet: Transparent, Allyl Base. Air Materiel Command, Wright-Patterson Air Force Base, Dayton, Ohio.

7. Air Materiel Command Manual No. 5-4; Preparation of Air Force Technical Reports (January, 1950). Air Materiel Command, Wright-Patterson Air Force Base, Dayton, Ohio.

8. Irvine C. Gardner, A Test of Lens Resolution for the Photographer; Circular of the National Bureau of Standards C428. Government Printing Office, Washington, D. C., 1941.

9. Modern Plastics Encyclopedia, Vol. 1, 1947 Edition. Plastics Catalogue Corp., New York 17, N. Y.

10. Tentative Method of Test for Heat Distortion Temperature of Plastics; Designation D648-45T. American Society for Testing Materials, Phila. 3, Penna.

11. Tentative Method of Test for Haze of Transparent Plastics by Photoelectric Cell; Designation D672-45T. American Society for Testing Materials, Phila. 3, Penna.

12. Brown Pneumatic System for Remote Transmission of Flow, Level, Temperature or Pressure Readings; Instruction Manual #3059, Issue 3. Brown Instrument Co., Phila. 44, Penna.

13. Brown Rectangular Case Indicating Pressure and Vacuum Gages; Instruction Manual #70001G, Issue 1. Brown Instrument Co., Phila. 44, Penna.

14. Brown Rectangular Case Electric Motion Transmitter; Instruction Manual #3095 Issue 7. Brown Instrument Co., Phila. 44, Penna.

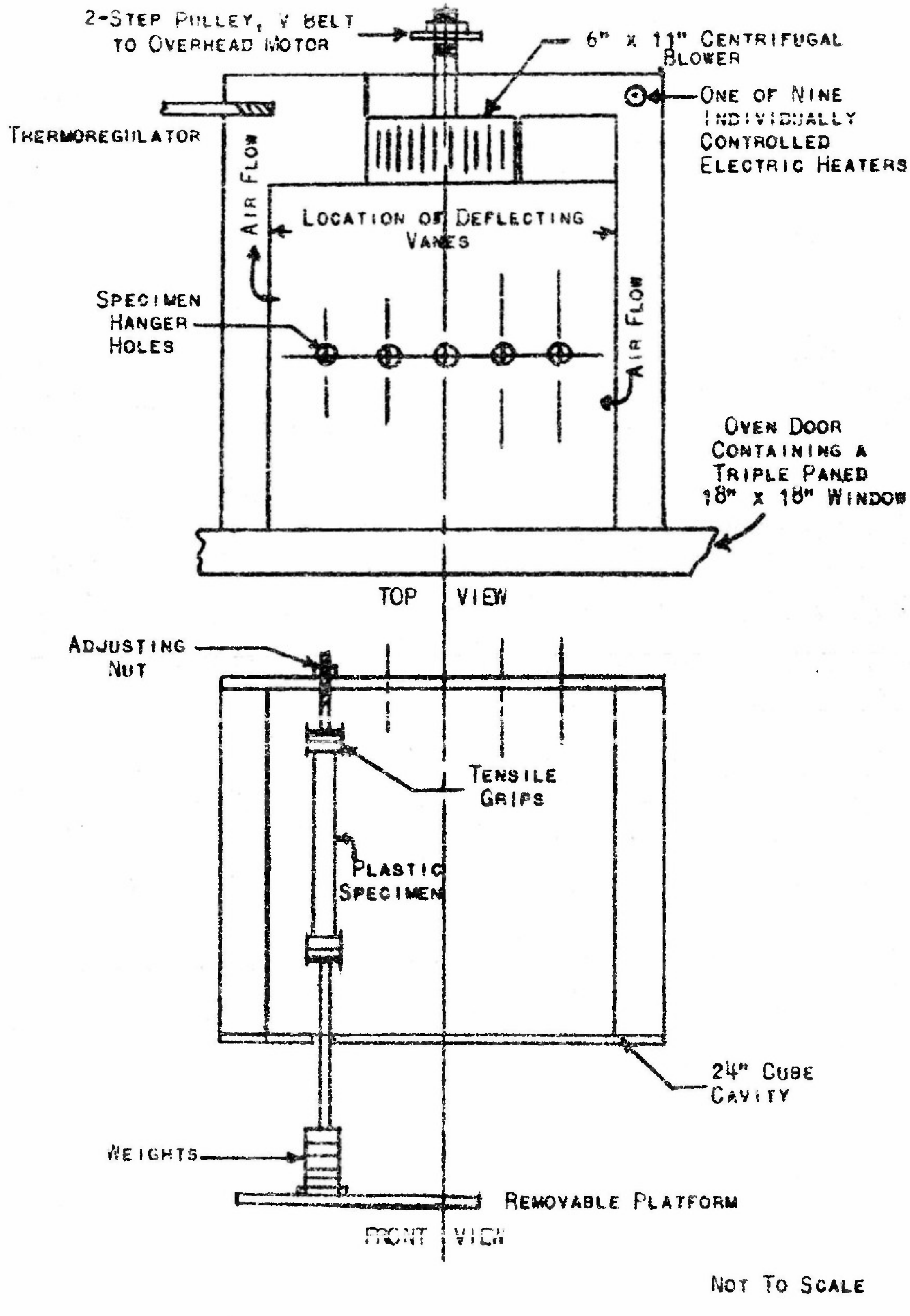


FIGURE 1. SCHEMATIC DIAGRAM OF EXPERIMENTAL OVEN SHOWING PLASTIC SPECIMEN TO BE MEASURED FOR ELONGATION RATE

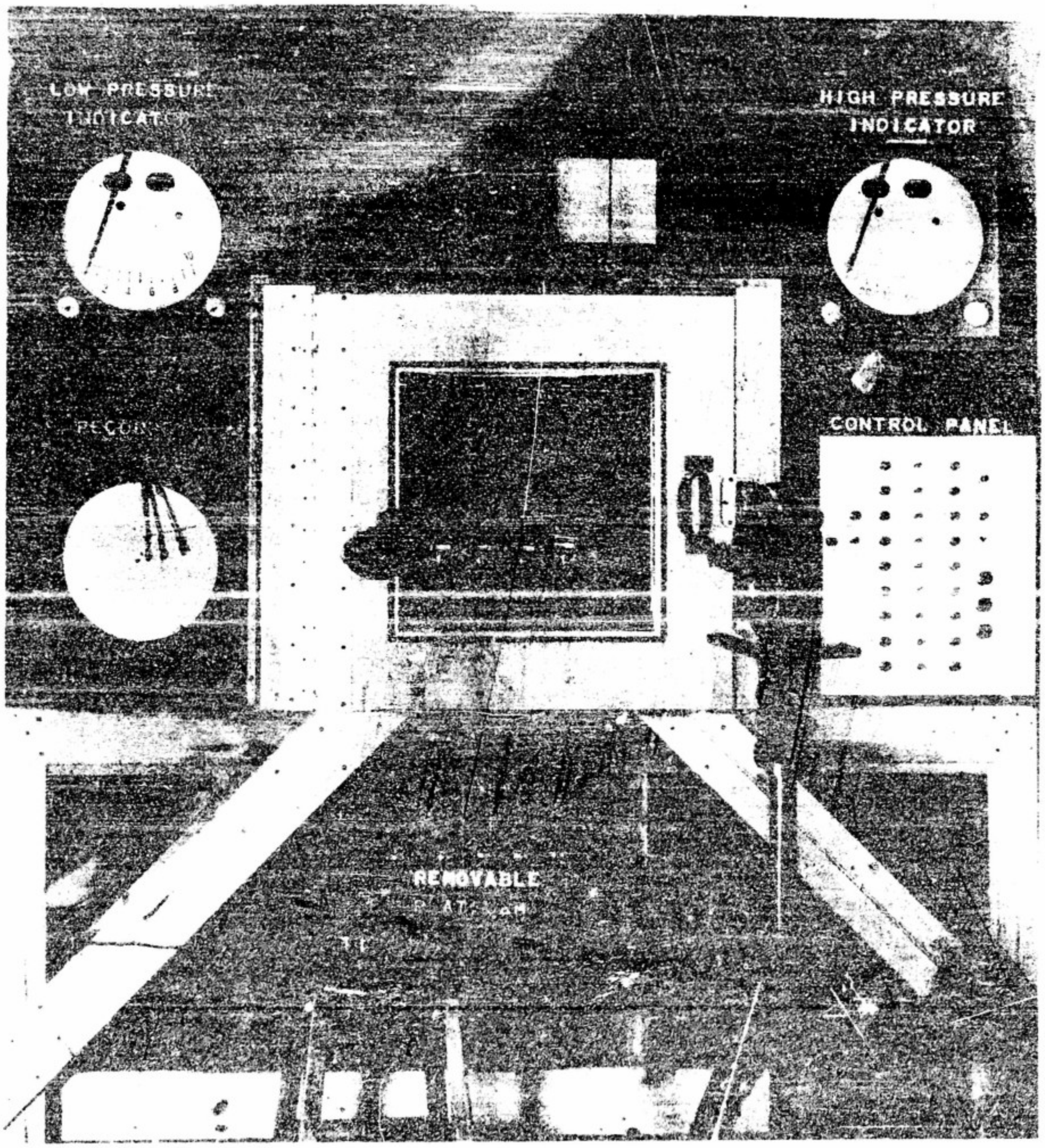


Figure 2 SET-UP USED TO MEASURE UNIAXIAL ELONGATION
RATE OF PLASTIC SPECIMENS IN EXPERIMENTAL OVEN

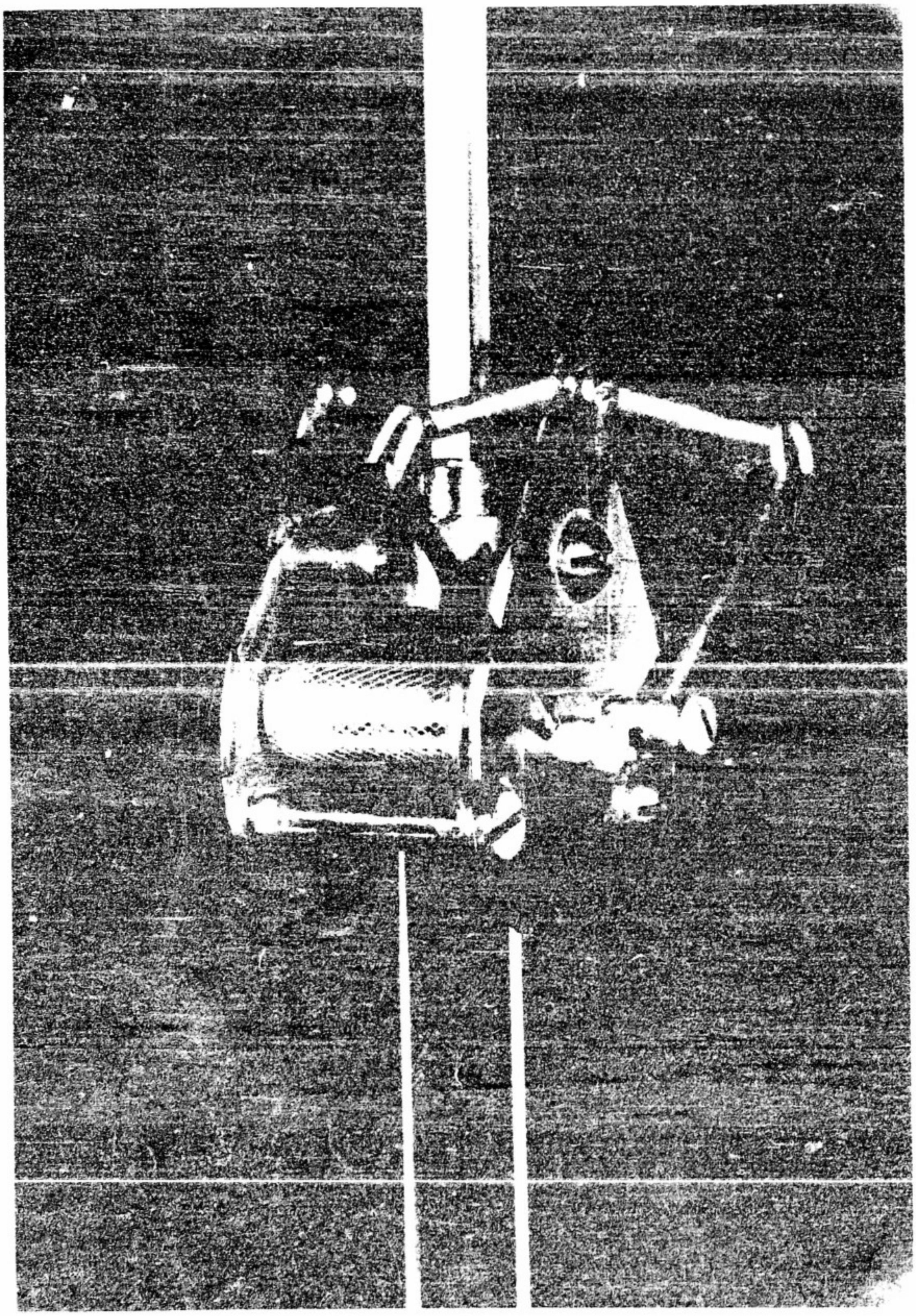


Figure 3 TENSILE GRIP FOR PLASTIC SPECIMENS

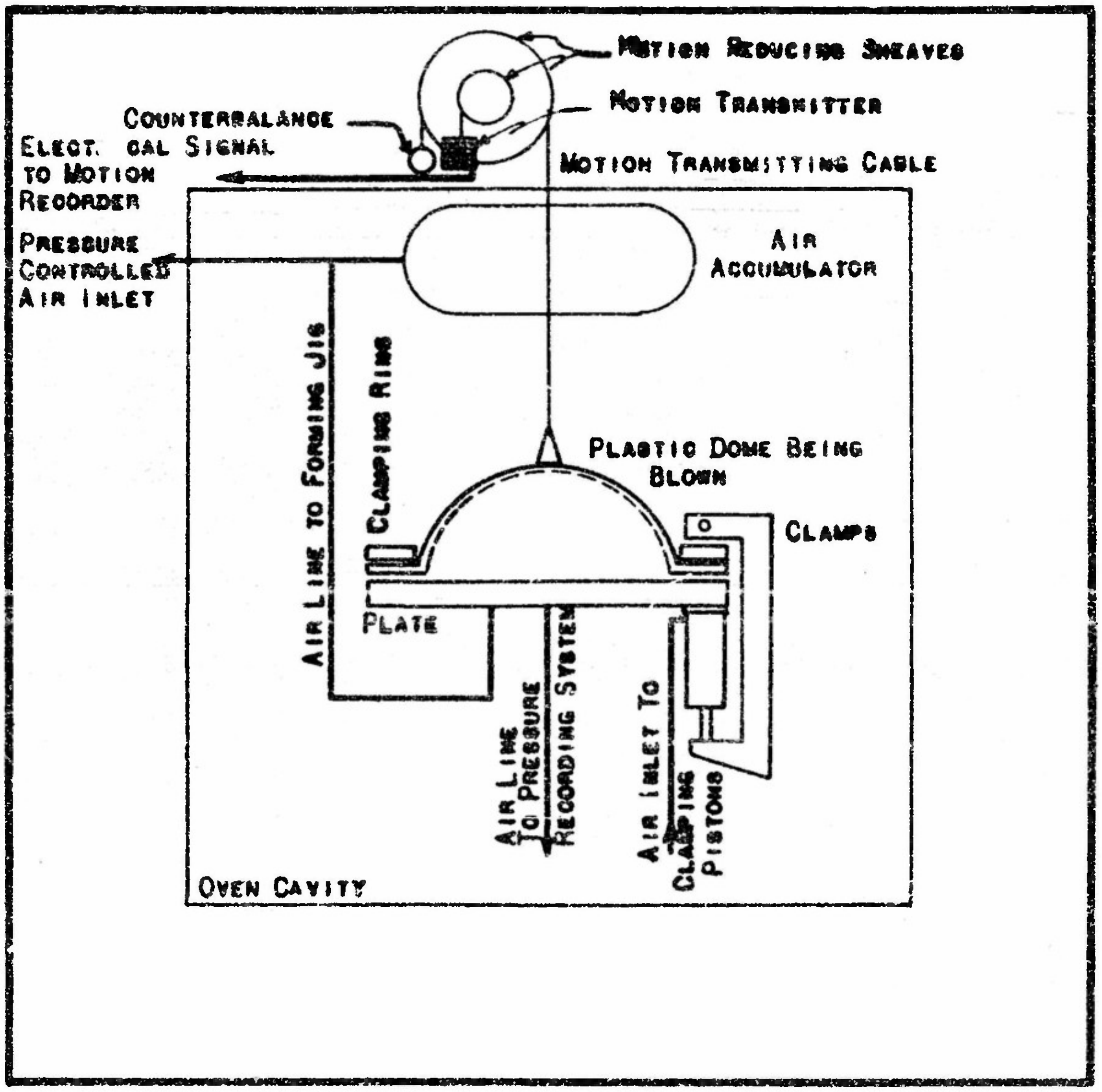


FIGURE 4. SCHEMATIC DIAGRAM OF EXPERIMENTAL OVEN SHOWING PLASTIC DOME BEING FORMED

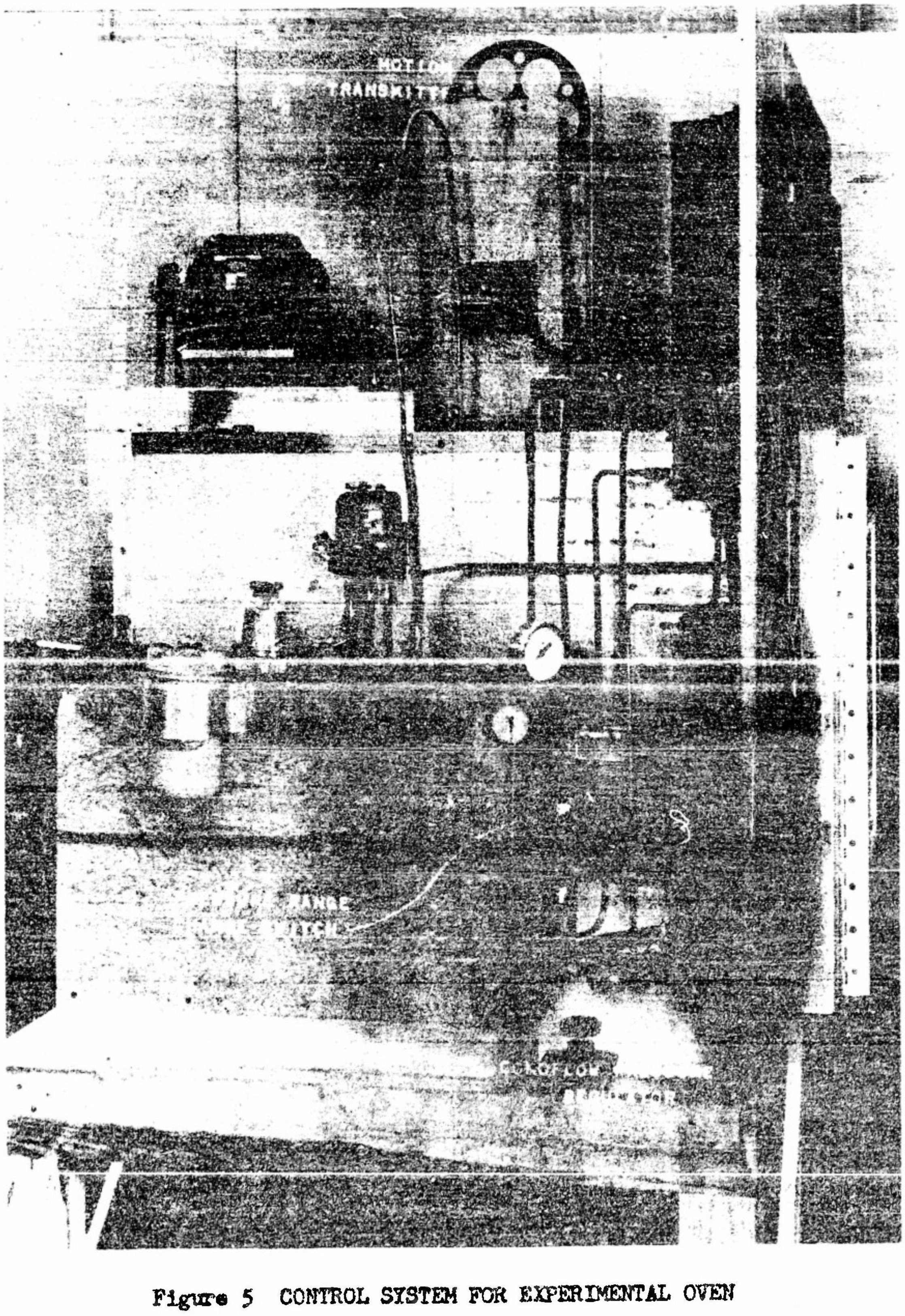


Figure 5 CONTROL SYSTEM FOR EXPERIMENTAL OVEN

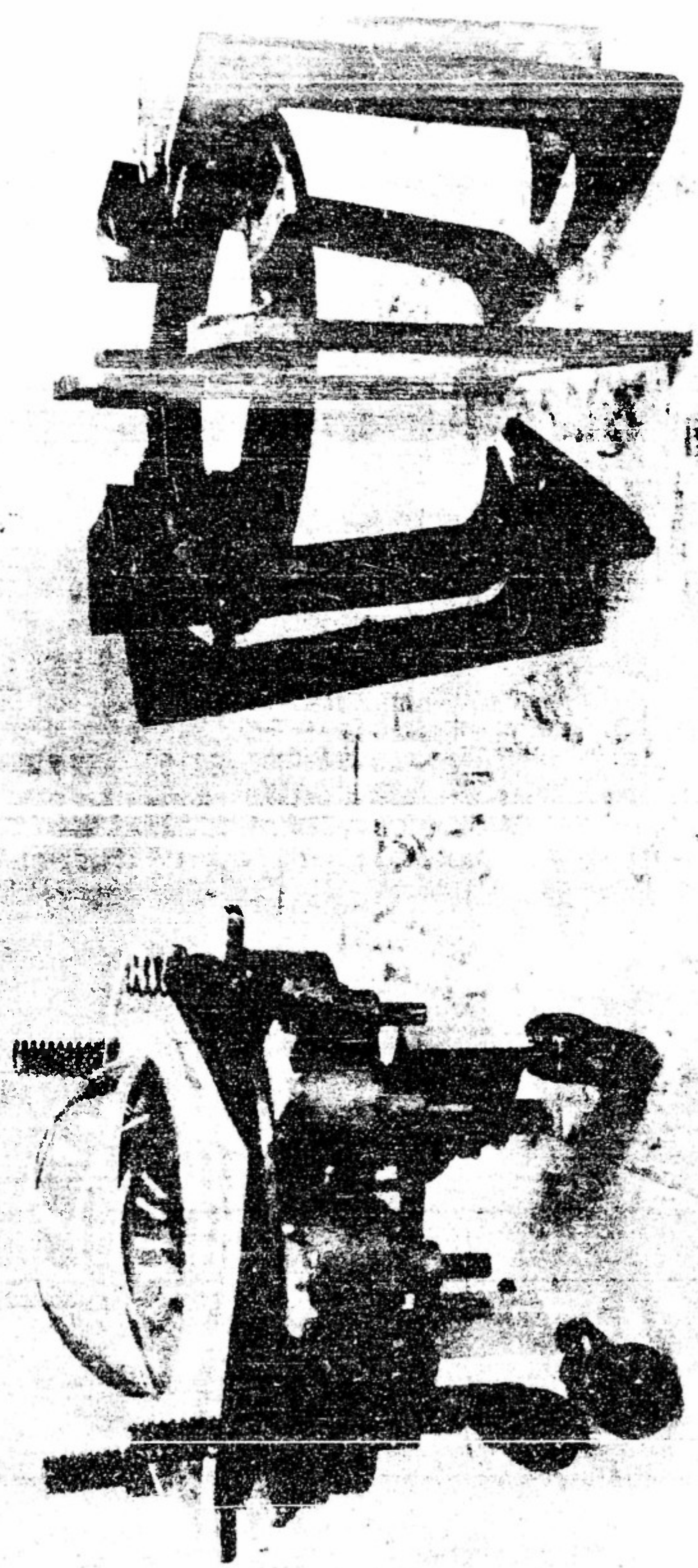


Figure 6 SPHERICAL FORMING FIXTURE

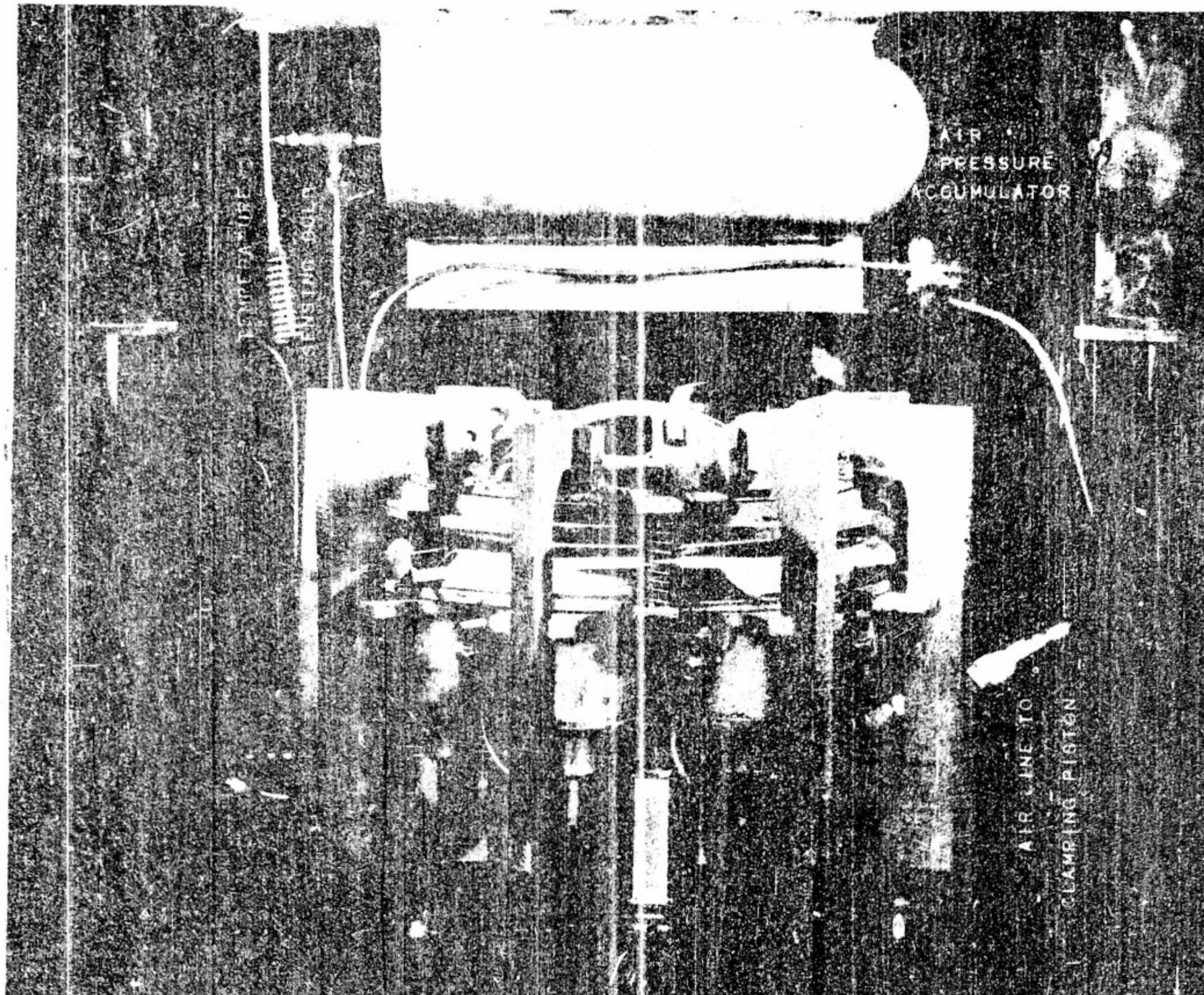


Figure 7 OVEN CAVITY WITH SPHERICAL FORMING FIXTURE

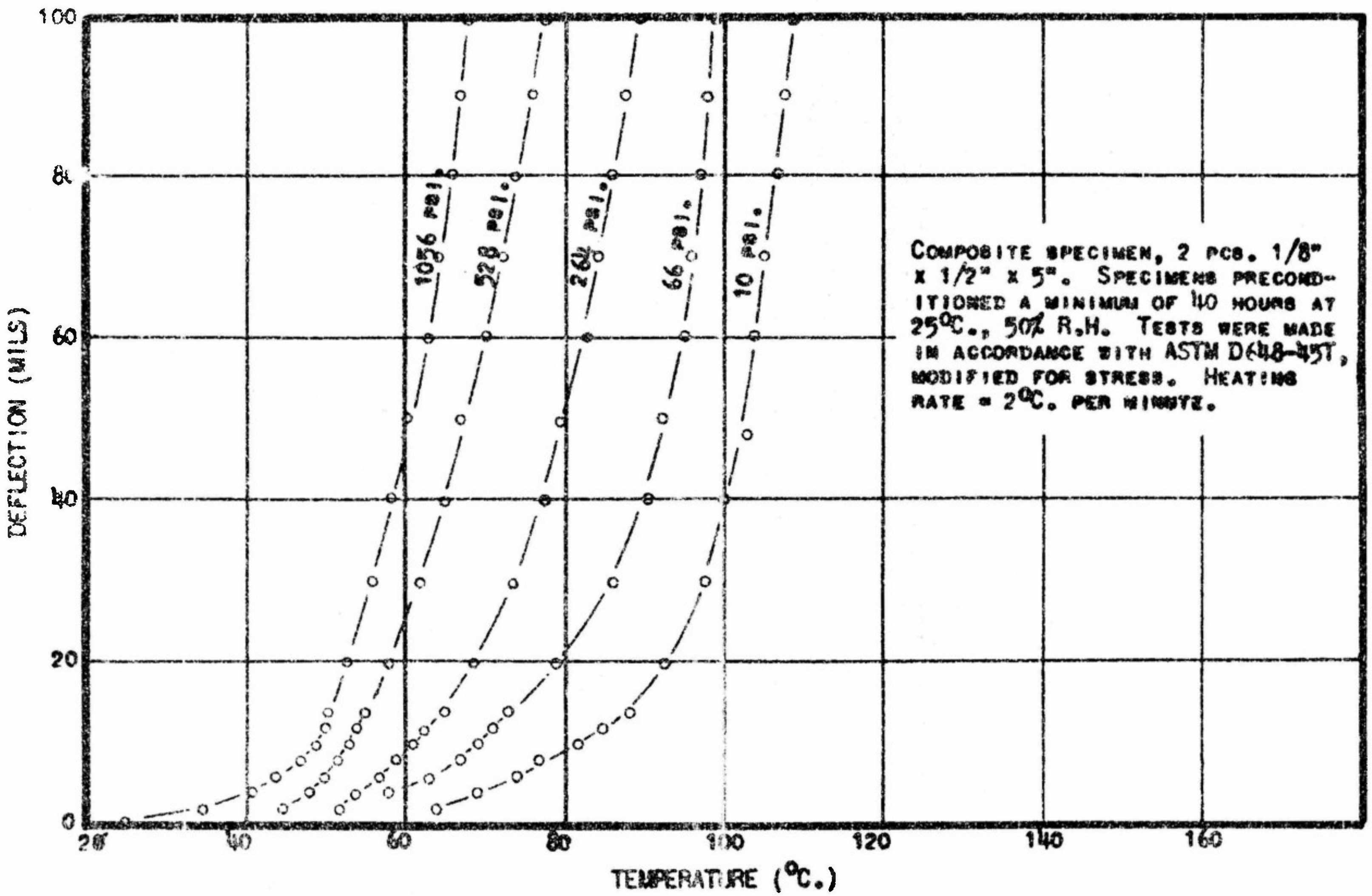


Figure 8. FLEXURAL DEFORMATION AT SEVERAL STRESSES VS. TEMPERATURE OF LUMARITH

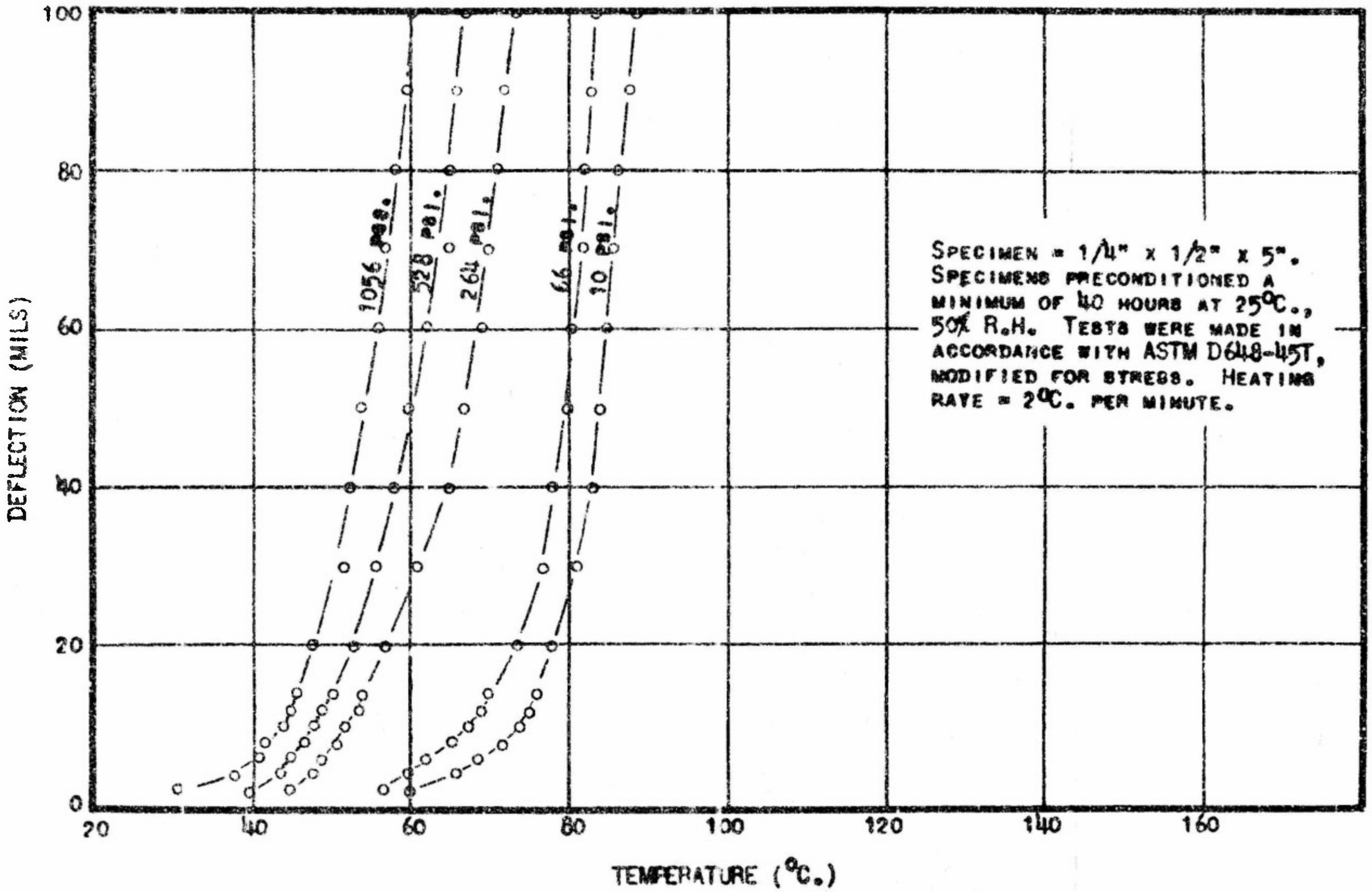


FIGURE 9. FLEXURAL DEFORMATION AT SEVERAL STRESSES VS. TEMPERATURE OF PLASTACELE

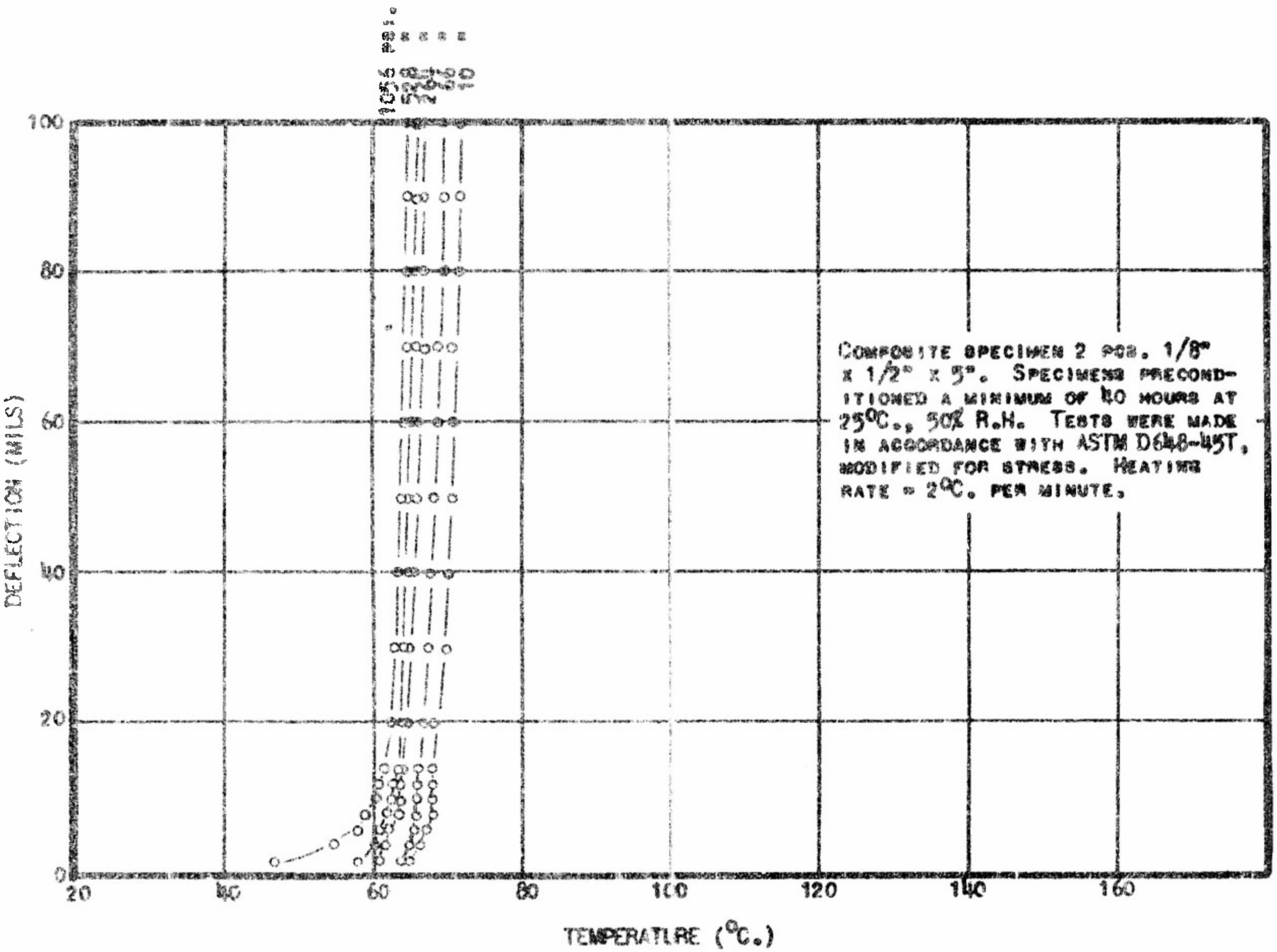


FIGURE 10. FLEXURAL DEFORMATION AT SEVERAL STRESS VS. TEMPERATURE OF VINYLITE

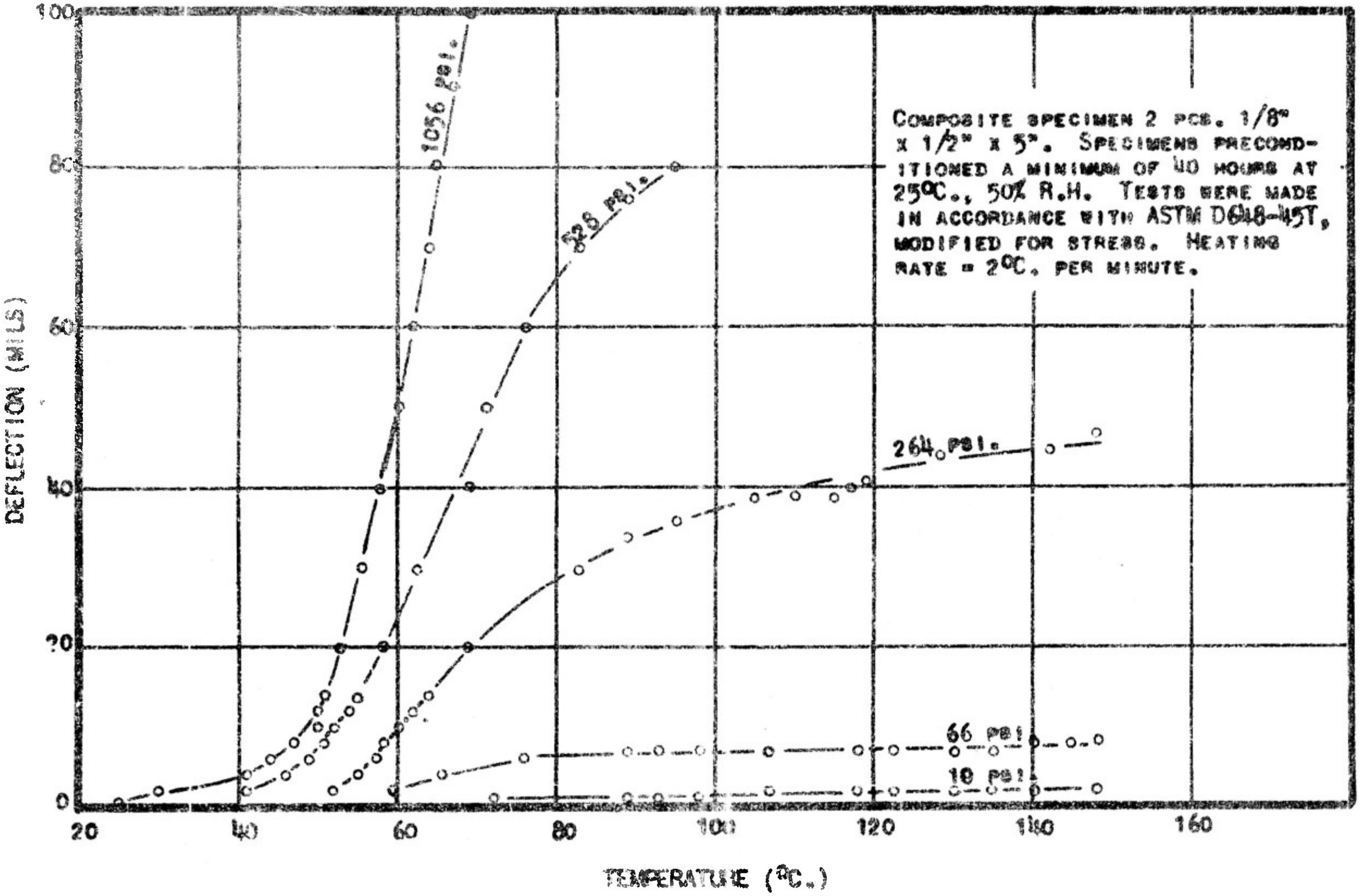


FIGURE 11. FLEXURAL DEFORMATION AT SEVERAL STRESSES VS. TEMPERATURE OF HOMALITE CR-39

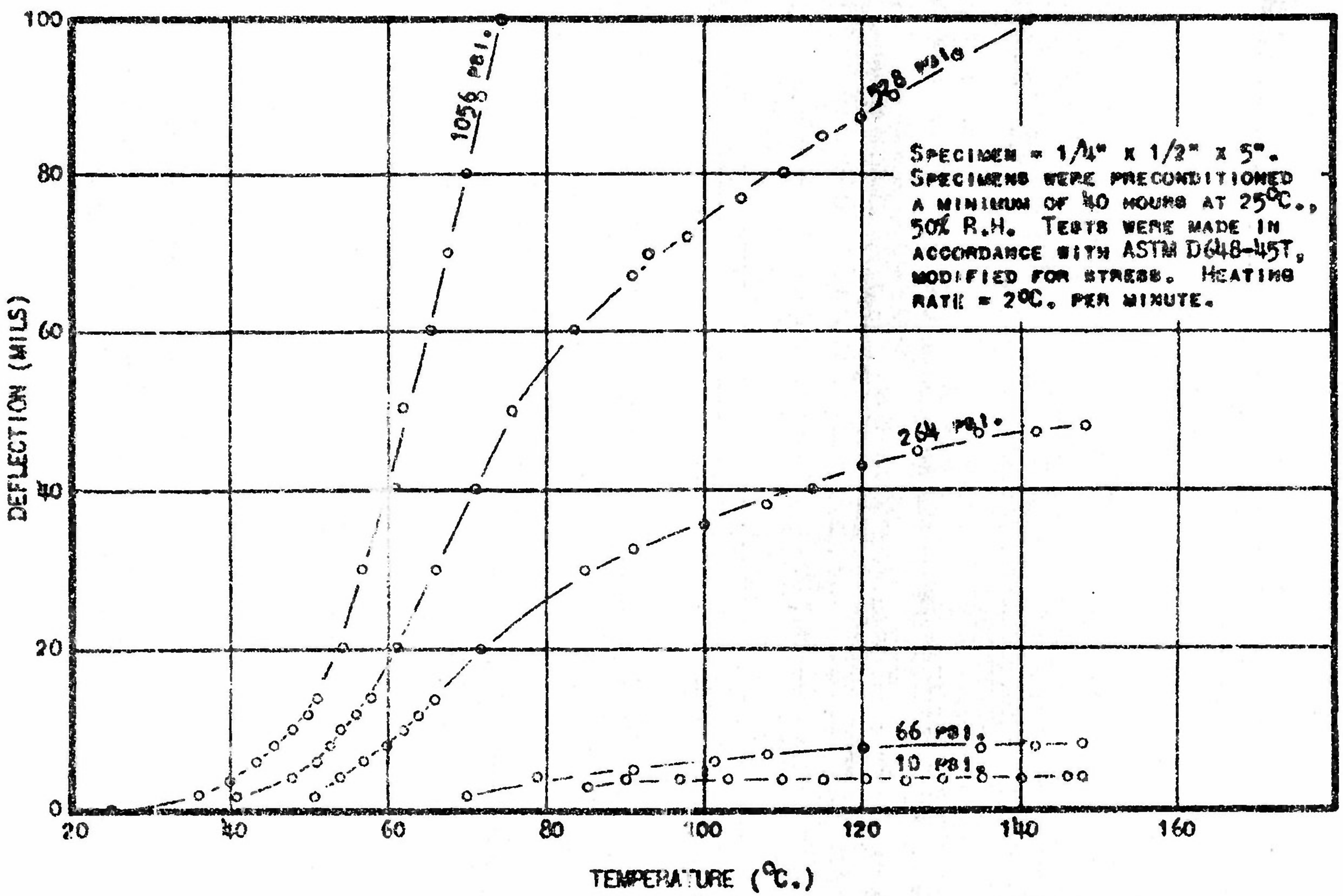


Figure 12. FLEXURAL DEFORMATION AT SEVERAL STRESSES VS. TEMPERATURE OF HOMALITE CR-39

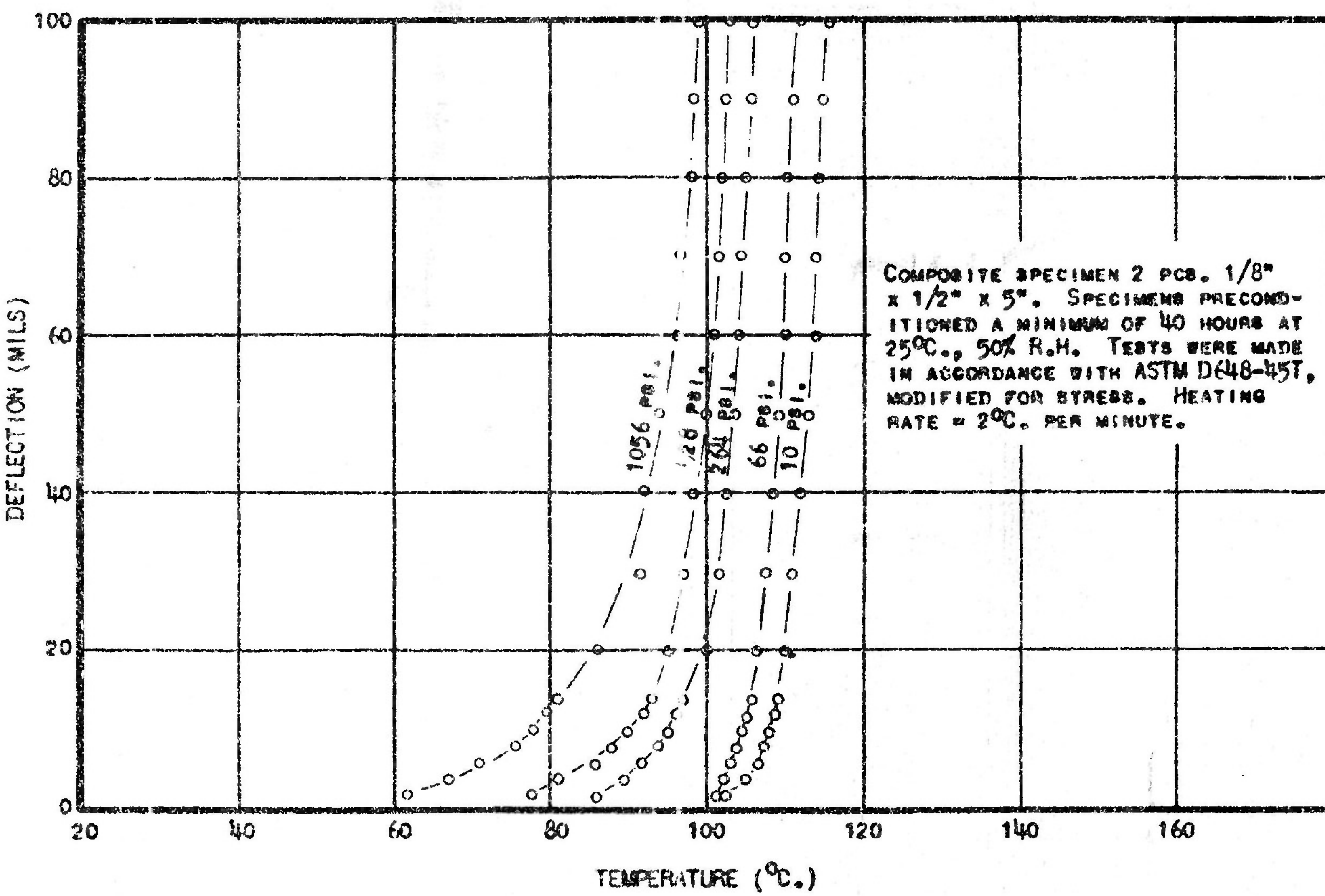


FIGURE 13. FLEXURAL DEFORMATION AT SEVERAL STRESSES VS. TEMPERATURE OF PLEXIGLAS II

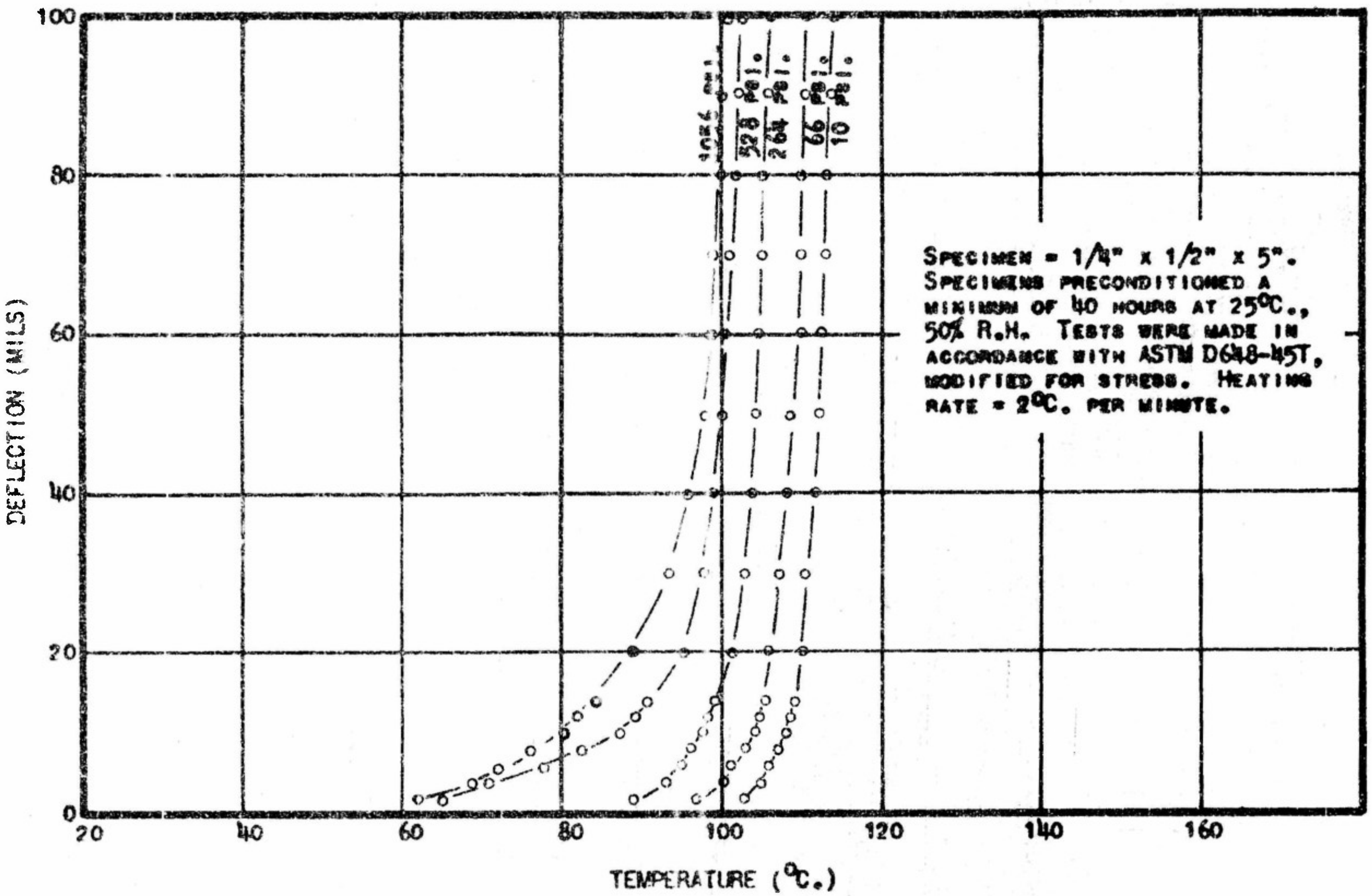


FIGURE 14. FLEXURAL DEFORMATION AT SEVERAL STRESSES VS. TEMPERATURE OF PLEXIGLAS II

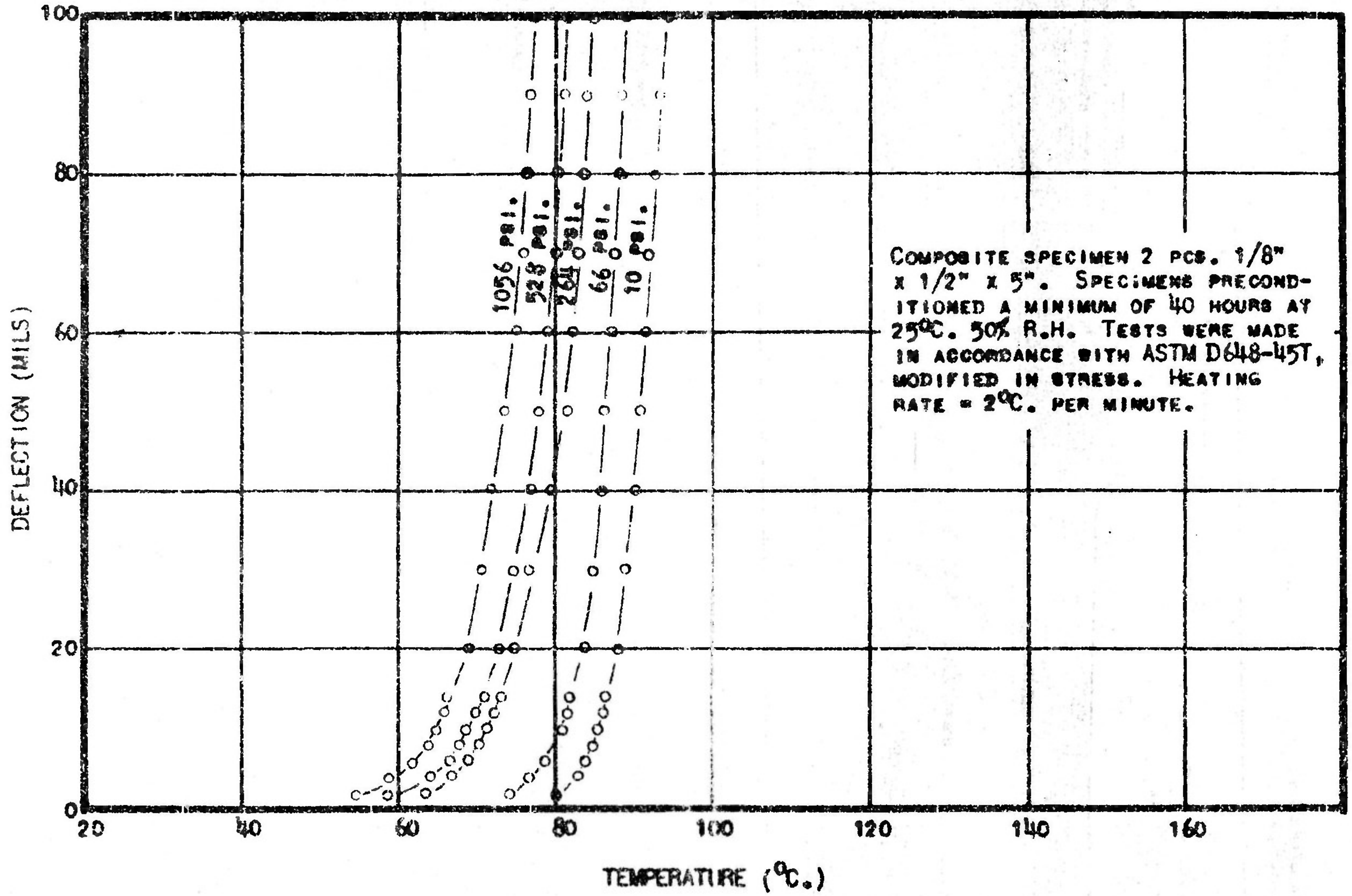


FIGURE 15. FLEXURAL DEFORMATION AT SEVERAL STRESSES VS. TEMPERATURE OF PLEXIGLAS I-A

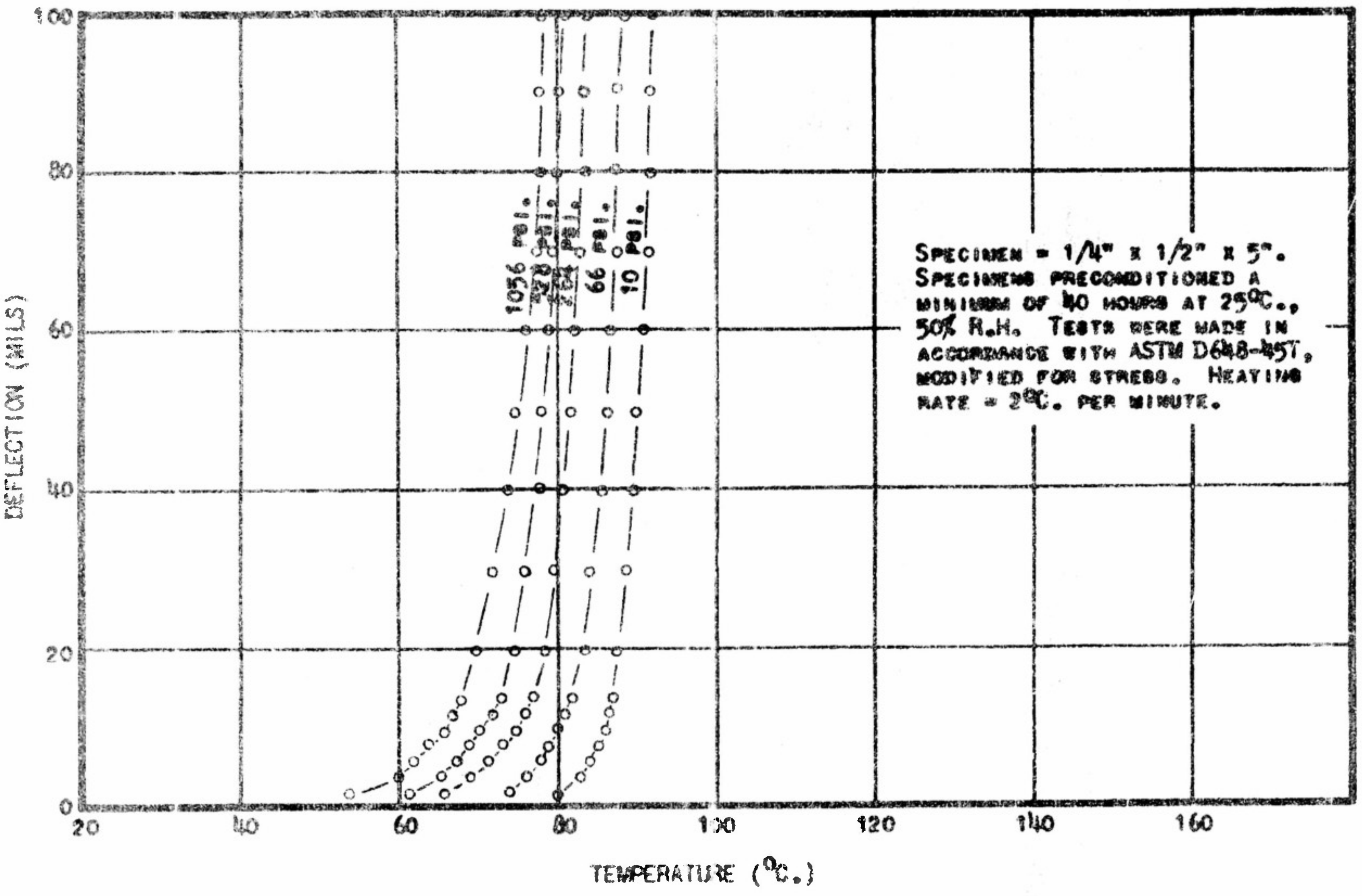


FIGURE 16. FLEXURAL DEFORMATION AT SEVERAL STRESSES VS. TEMPERATURE OF PLEXIGLAS I-A

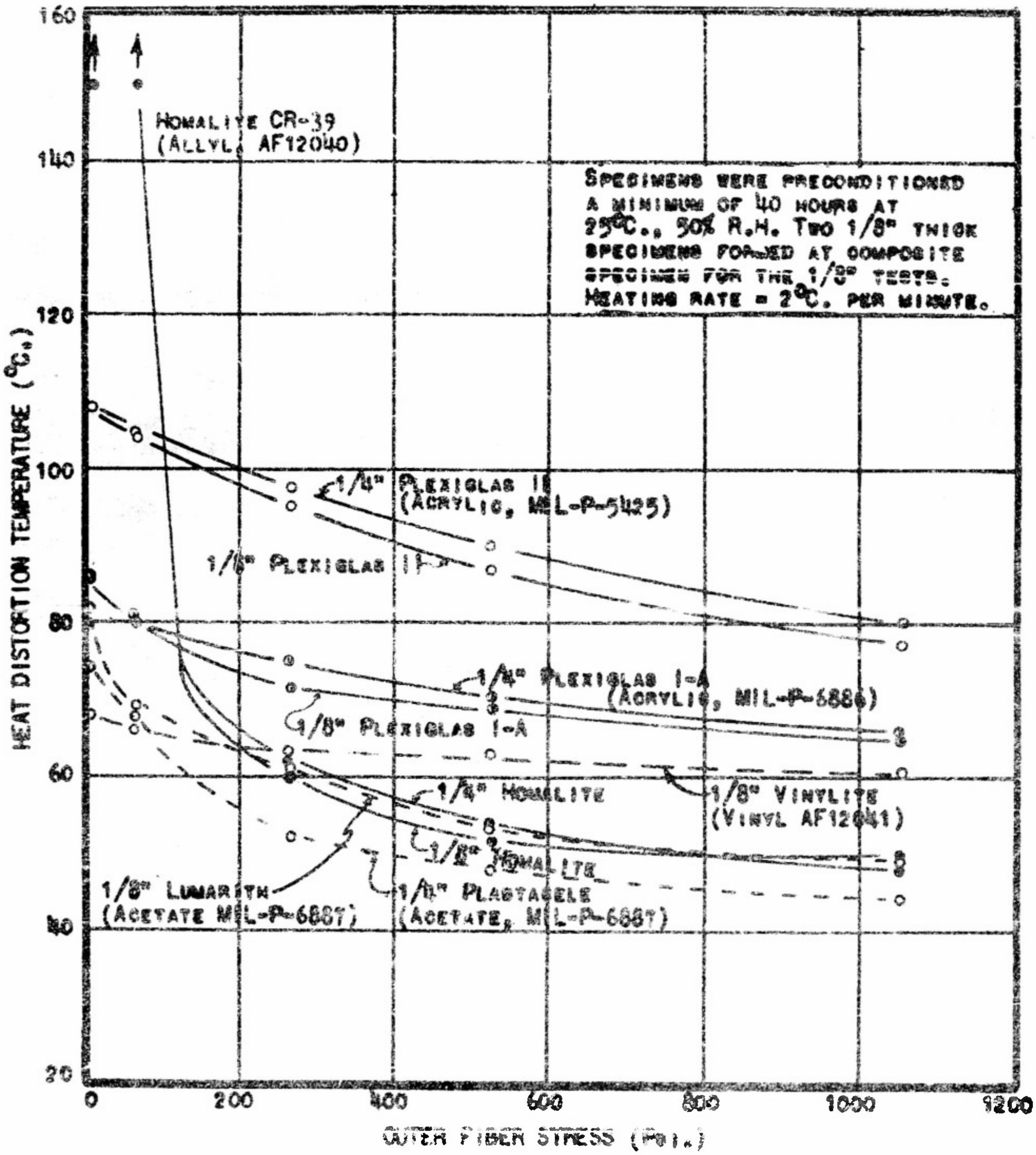


FIGURE 17. HEAT DISTORTION TEMPERATURE VS. APPLIED OUTER FIBER STRESS (ASTM METHOD D648-45T, MODIFIED FOR STRESS, 10 MIL DEFLECTION)

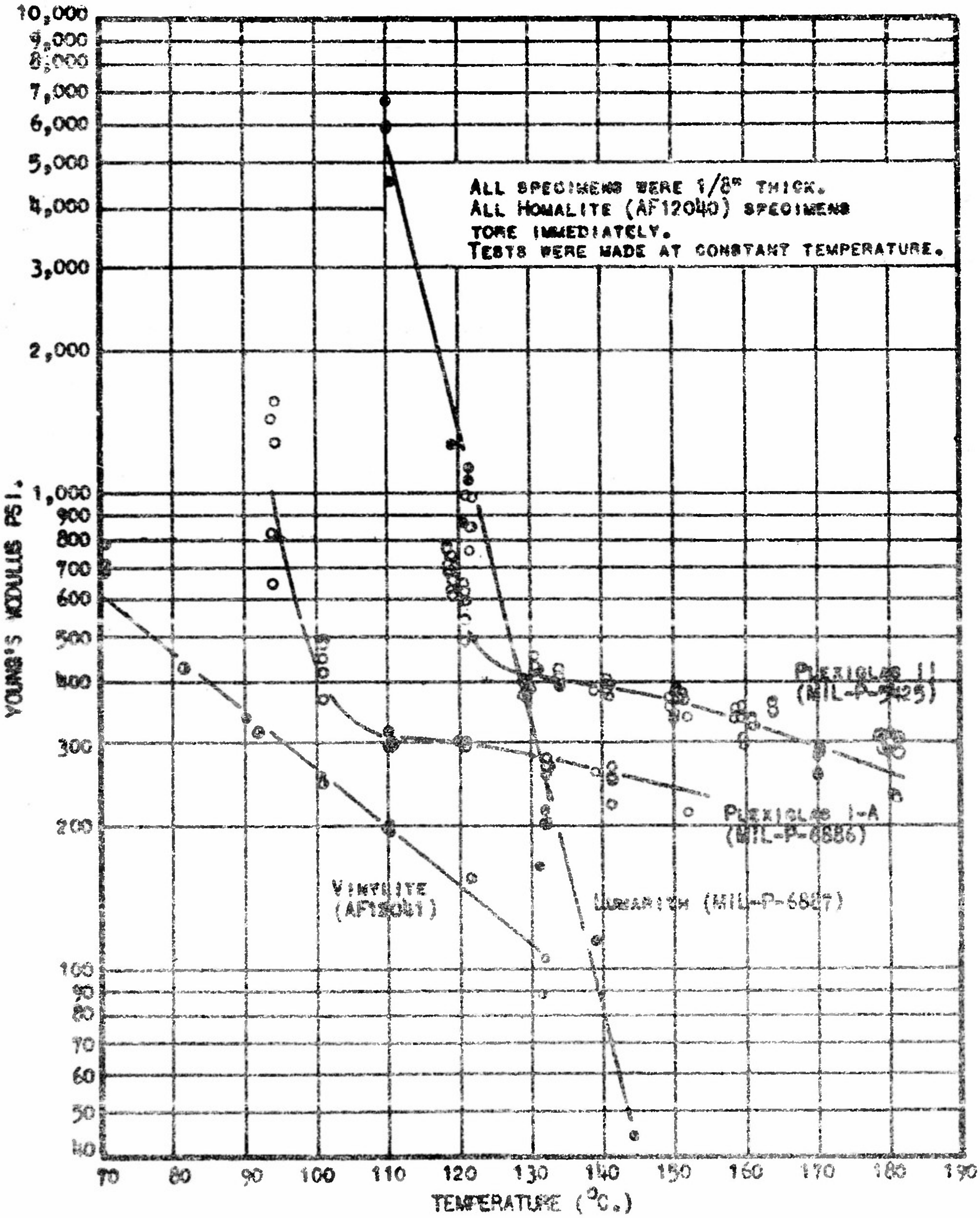
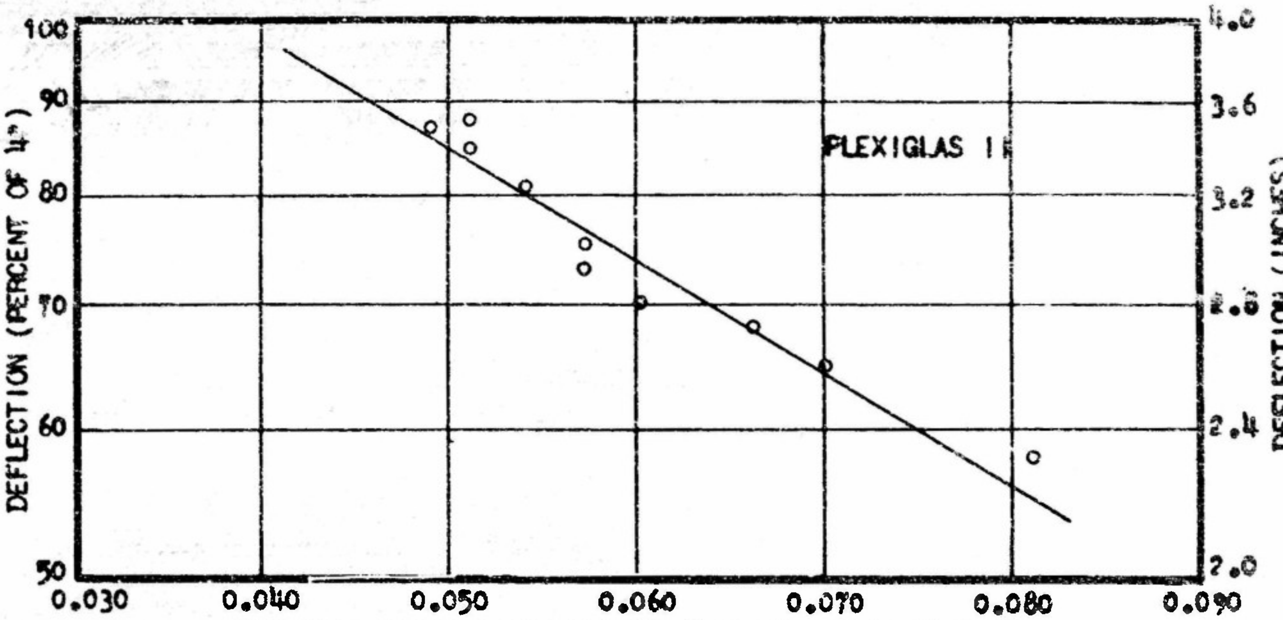
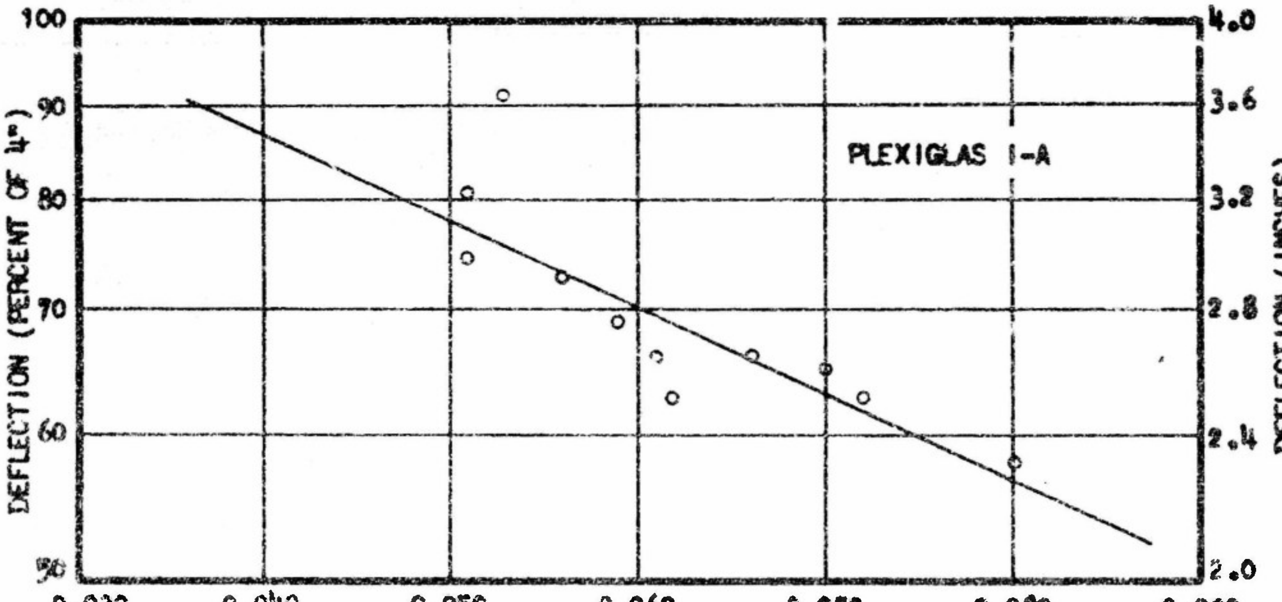


FIGURE 18. MODULUS OF ELASTICITY IN TENSION 30 SECONDS AFTER APPLICATION OF LOAD VS. TEMPERATURE OF VARIOUS TRANSPARENT PLASTIC MATERIALS



AVERAGE CENTER THICKNESS OF ORIGINAL SHEET (INCHES)

FIGURE 19 (TEMPERATURE = 135°C. (275°F.), PRESSURE = 2.75 PSI.)



AVERAGE CENTER THICKNESS OF ORIGINAL SHEET (INCHES)

FIGURE 20 (TEMPERATURE = 135°C. (275°F.), PRESSURE = 1.75 PSI.)

<u>CENTER DEFLECTION VS. INITIAL AVERAGE CENTER THICKNESS OF PLEXIGLAS I-A AND PLEXIGLAS II 8" DIAMETER SPHERICAL SECTIONS</u>

(SPECIMENS AT CONSTANT TEMPERATURE, DEFLECTION MEASURED THREE MINUTES AFTER APPLICATION OF CONSTANT AIR PRESSURE.)

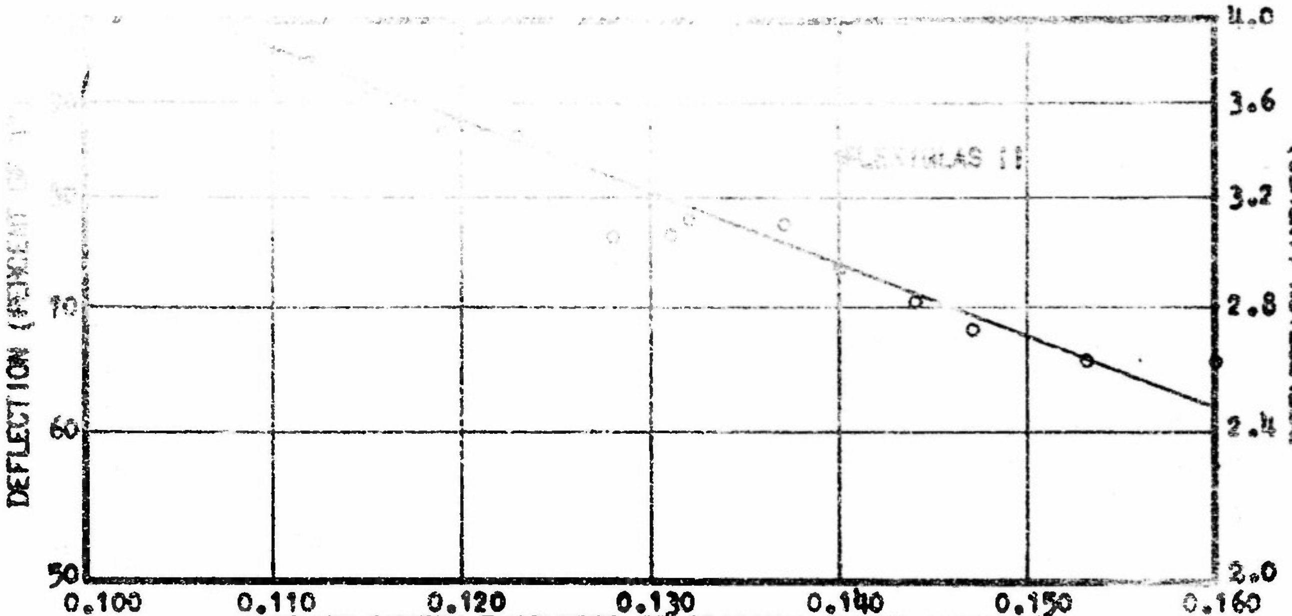


FIGURE 21 (TEMPERATURE = 135°C. (275°F.), PRESSURE = 6.75 PSI.)

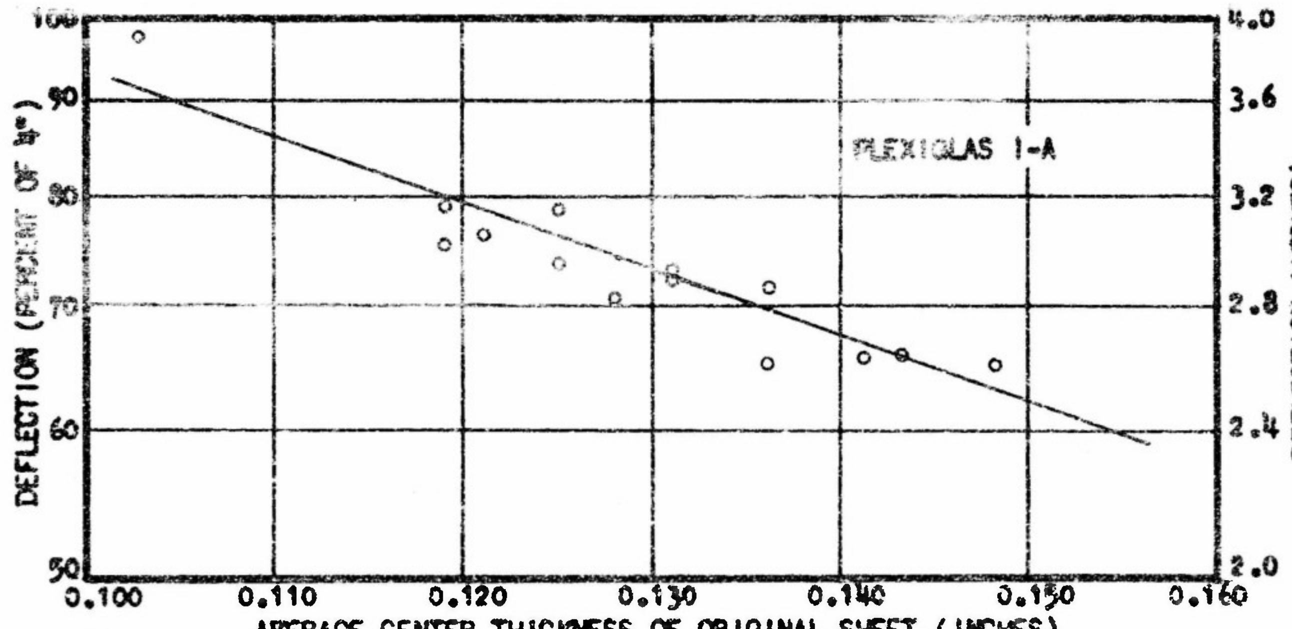


FIGURE 22 (TEMPERATURE = 135°C. (275°F.), PRESSURE = 3.75 PSI.)

<u>CENTER DEFLECTION VS. INITIAL AVERAGE CENTER THICKNESS OF PLEXIGLAS I-A AND PLEXIGLAS II 8" DIAMETER SPHERICAL SECTIONS</u>

(SPECIMENS AT CONSTANT TEMPERATURE, DEFLECTION MEASURED THREE MINUTES AFTER APPLICATION OF CONSTANT AIR PRESSURE.)

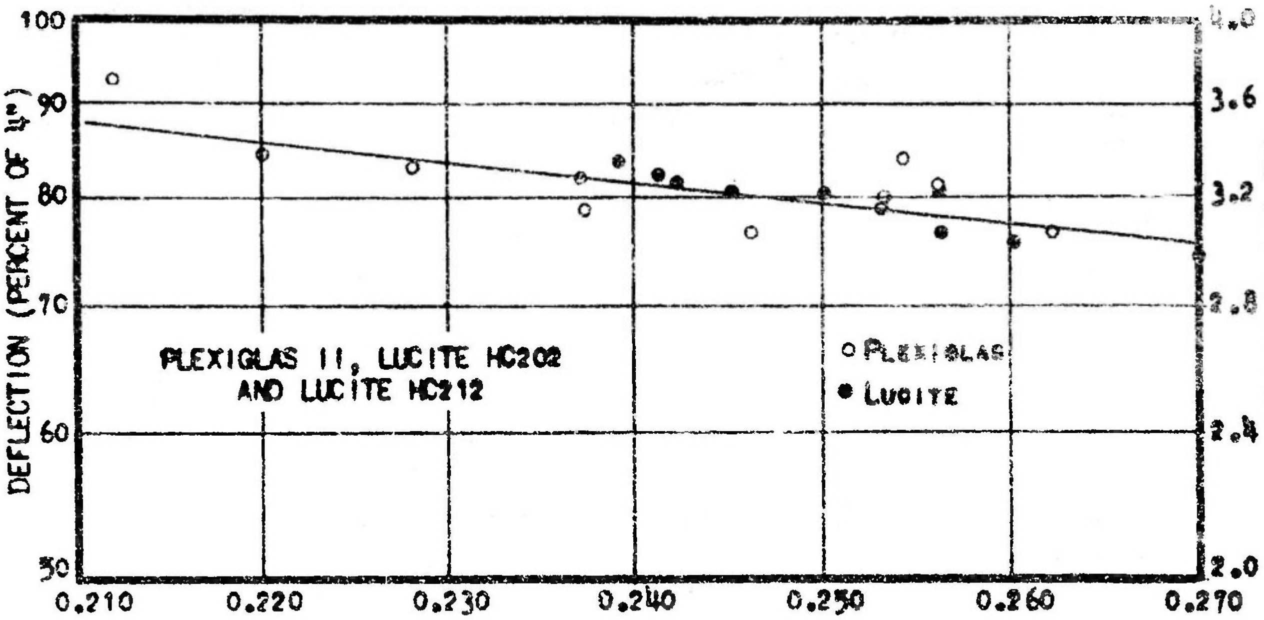


FIGURE 23 (TEMPERATURE = 135°C. (275°F.), PRESSURE = 13.5 PSI.)

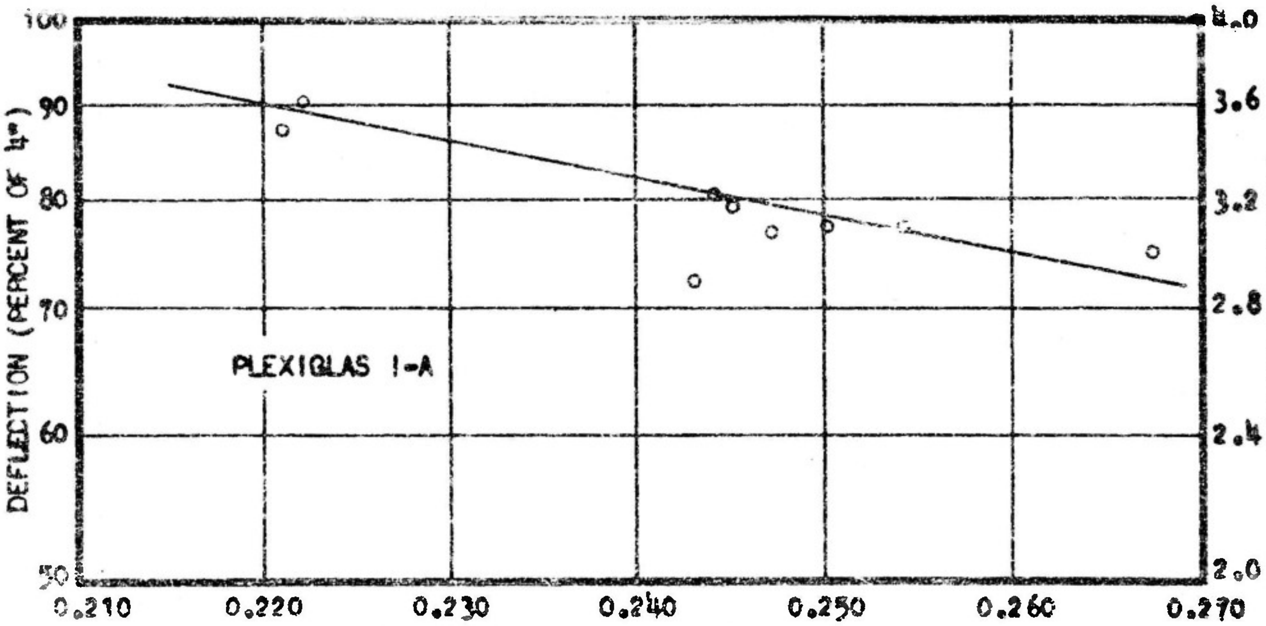


FIGURE 24 (TEMPERATURE = 135°C. (275°F.), PRESSURE = 7.5 PSI.)

CENTER DEFLECTION VS. INITIAL AVERAGE CENTER THICKNESS OF PLEXIGLAS I-A, PLEXIGLAS II, LUCITE HC202 AND LUCITE HC212 8" DIAMETER SPHERICAL SECTIONS

(SPECIMENS AT CONSTANT TEMPERATURE, DEFLECTION MEASURED THREE MINUTES AFTER APPLICATION OF CONSTANT AIR PRESSURE)

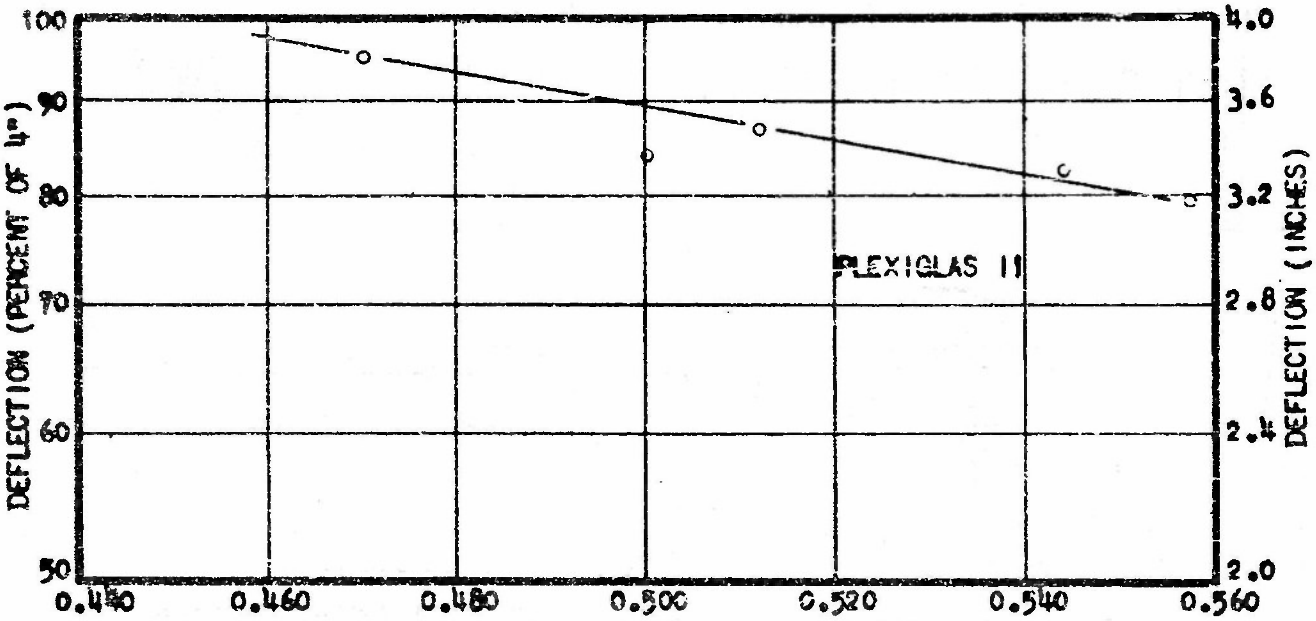


Figure 25 (Temperature = 135°C. (275°F.), Pressure = 27 Psi.)

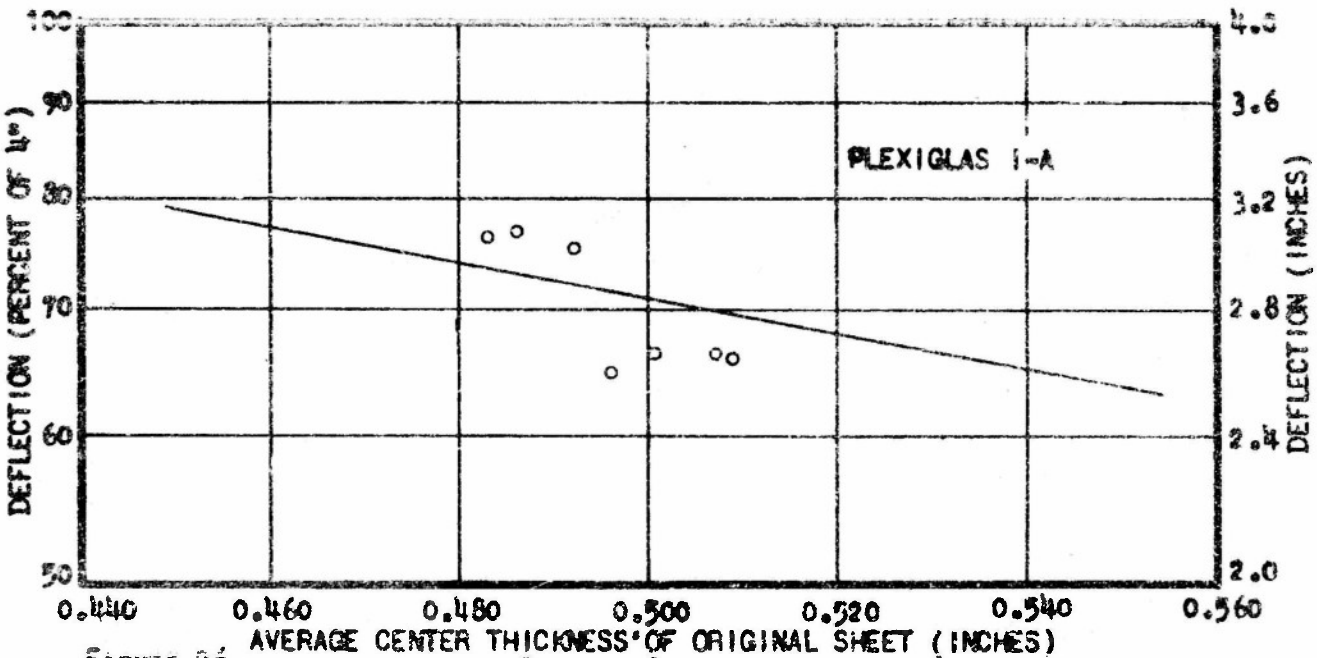
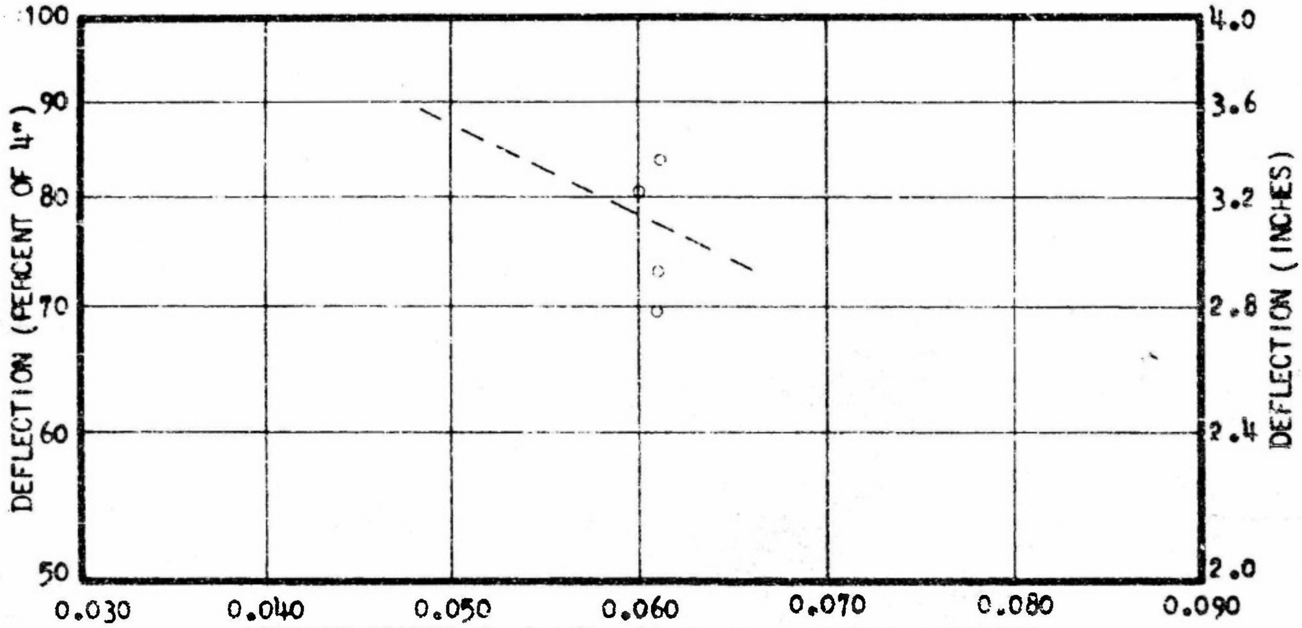


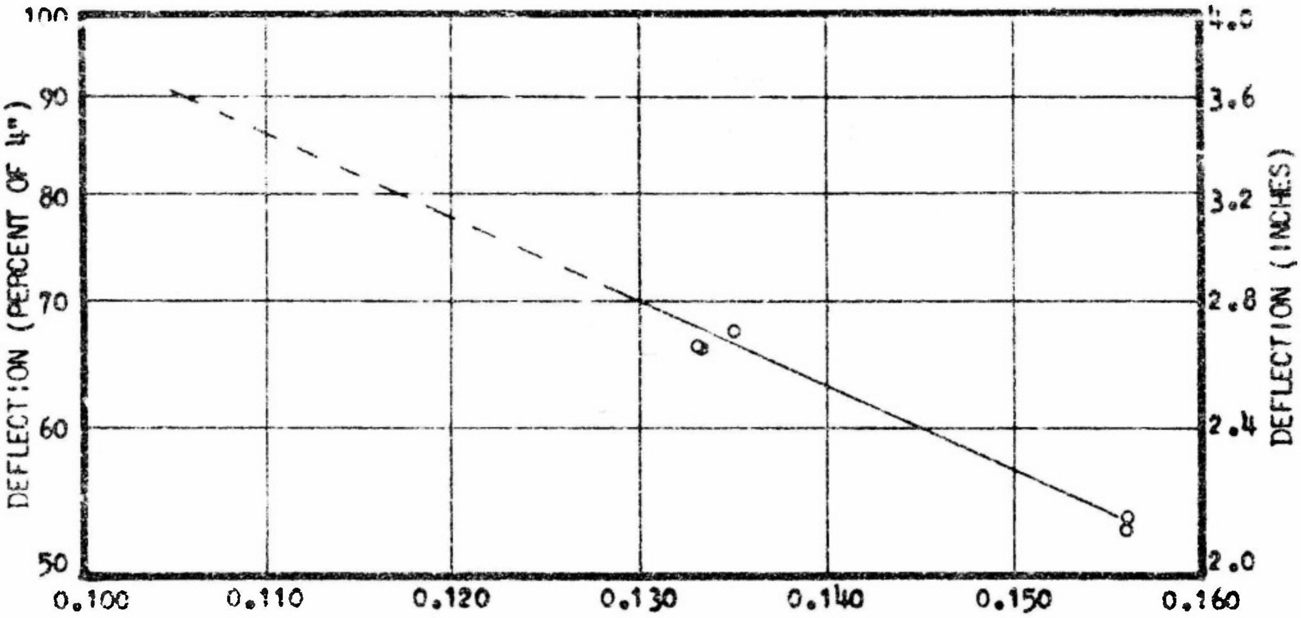
Figure 26 (Temperature = 135°C. (275°F.), Pressure = 15.2 Psi.)

CENTER DEFLECTION VS. INITIAL AVERAGE CENTER THICKNESS OF PLEXIGLAS I-A AND PLEXIGLAS II 8" DIAMETER SPHERICAL SECTIONS
(Specimens at Constant Temperature, Deflection Measured Three Minutes After Application of Constant Air Pressure)



AVERAGE CENTER THICKNESS OF ORIGINAL SHEET (INCHES)

FIGURE 27 (TEMPERATURE = 86°C. (187°F.), PRESSURE = 2 PSI.)



AVERAGE CENTER THICKNESS OF ORIGINAL SHEET (INCHES)

FIGURE 28 (TEMPERATURE = 86°C. (187°F), PRESSURE = 4.5 PSI.)

DEFLECTION VS. INITIAL AVERAGE CENTER THICKNESS OF VINYLITE 8" DIAMETER SPHERICAL SECTIONS

(SPECIMENS AT CONSTANT TEMPERATURE, DEFLECTION MEASURED THREE MINUTES AFTER APPLICATION OF CONSTANT AIR PRESSURE)

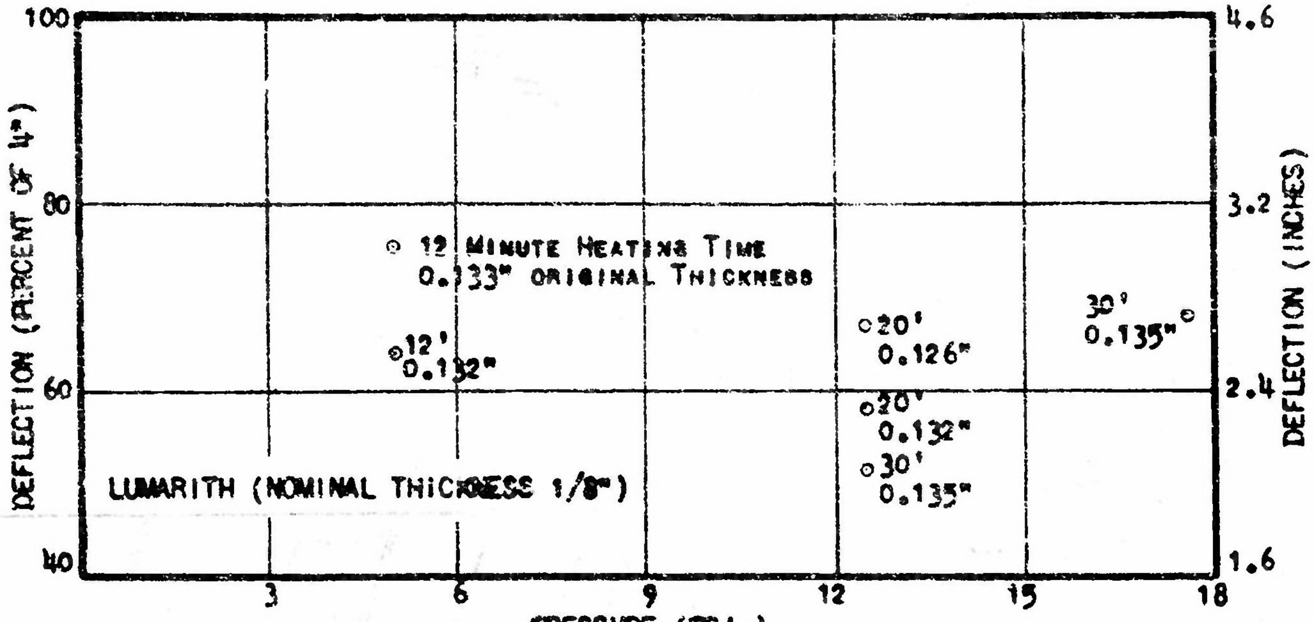


FIGURE 29

(TEMPERATURE 114°C. (237°F.)

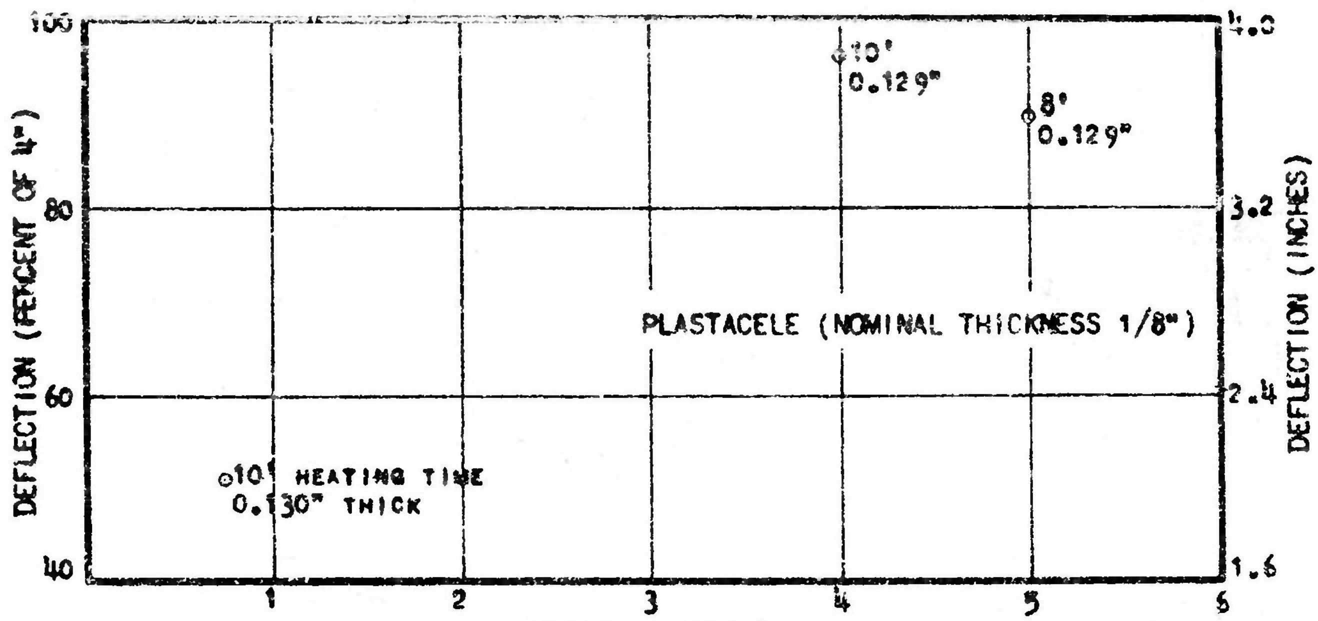


FIGURE 30

(TEMPERATURE 114°C. (237°F.)

CENTER DEFLECTION VS. FORMING PRESSURE OF 8" DIAMETER.
SPHERICAL SECTIONS OF CELLULOSE ACETATE

(SPECIMENS AT CONSTANT TEMPERATURE, DEFLECTION MEASURED THREE MINUTES AFTER APPLICATION OF CONSTANT AIR PRESSURE. HEATING TIME PRIOR TO FORMING AND INITIAL AVERAGE CENTER THICKNESS AS INDICATED.)

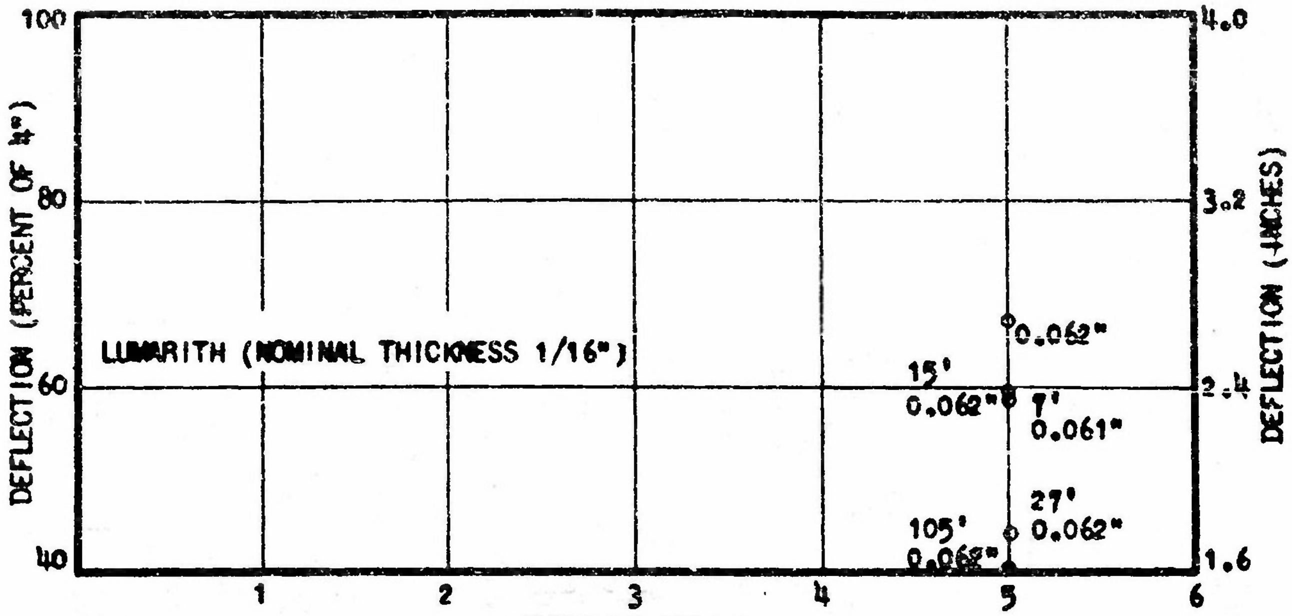


FIGURE 31

PRESSURE (PSI.)
(TEMPERATURE 114°C. (237°F.)

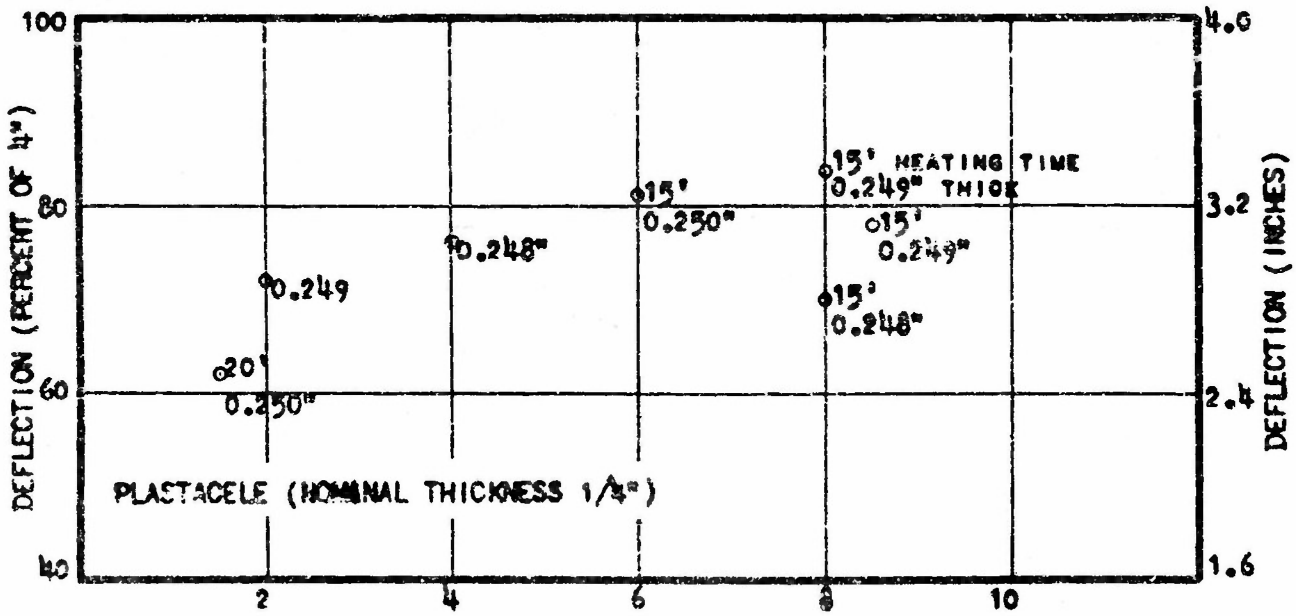
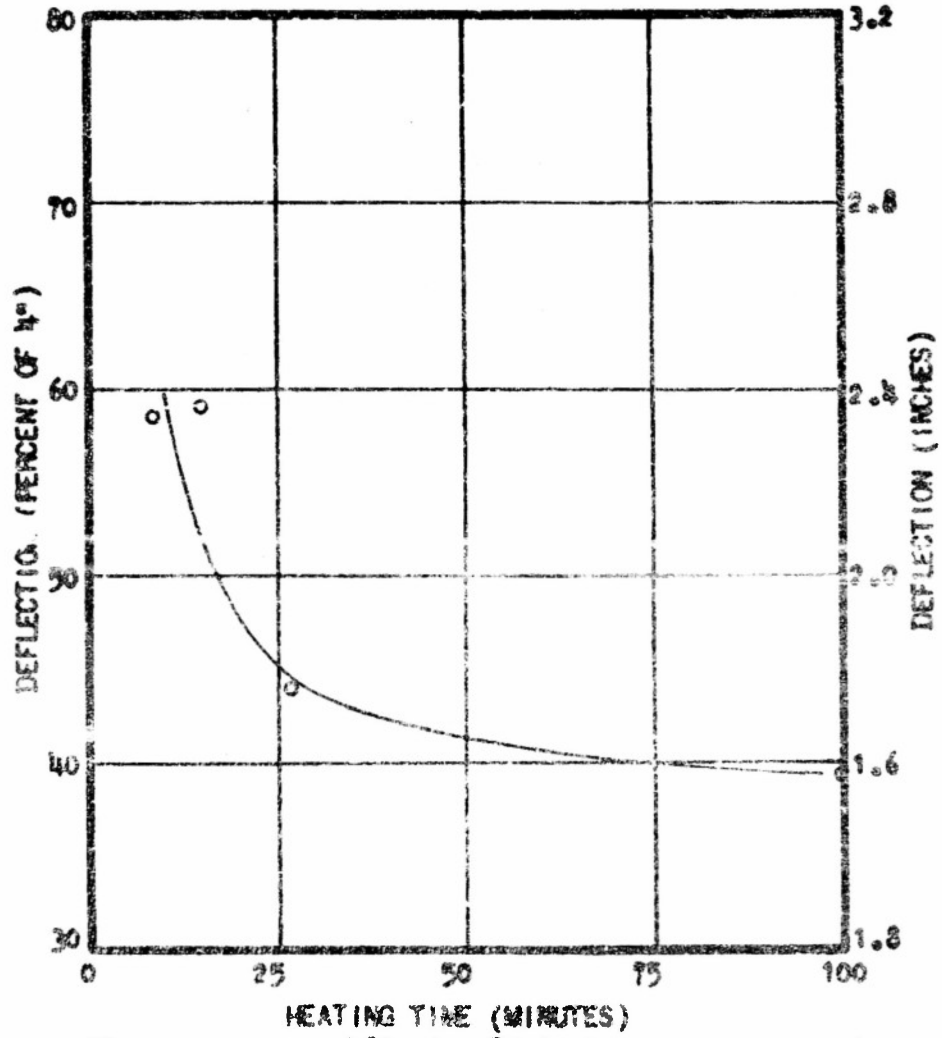


FIGURE 32

PRESSURE (PSI.)
(TEMPERATURE 114°C. (237°F.)

CENTER DEFLECTION VS. FORMING PRESSURE OF 8" DIAMETER,
SPHERICAL SECTIONS OF CELLULOSE ACETATE

(SPECIMENS AT CONSTANT TEMPERATURE, DEFLECTION MEASURED THREE MINUTES AFTER APPLICATION OF CONSTANT AIR PRESSURE. HEATING TIME PRIOR TO FORMING AND INITIAL AVERAGE CENTER THICKNESS AS INDICATED.)



(TEMPERATURE = 114°C. (237°F.), PRESSURE = 5 PSI.)

FIGURE 33. EFFECT OF VARYING HEATING TIME PRIOR TO FORMING 8" DIAMETER SPHERICAL SECTIONS OF 1/16" THICK [illegible]

(SPECIMENS AT CONSTANT TEMPERATURE, DEFLECTION MEASURED THREE MINUTES AFTER APPLICATION OF CONSTANT AIR PRESSURE)

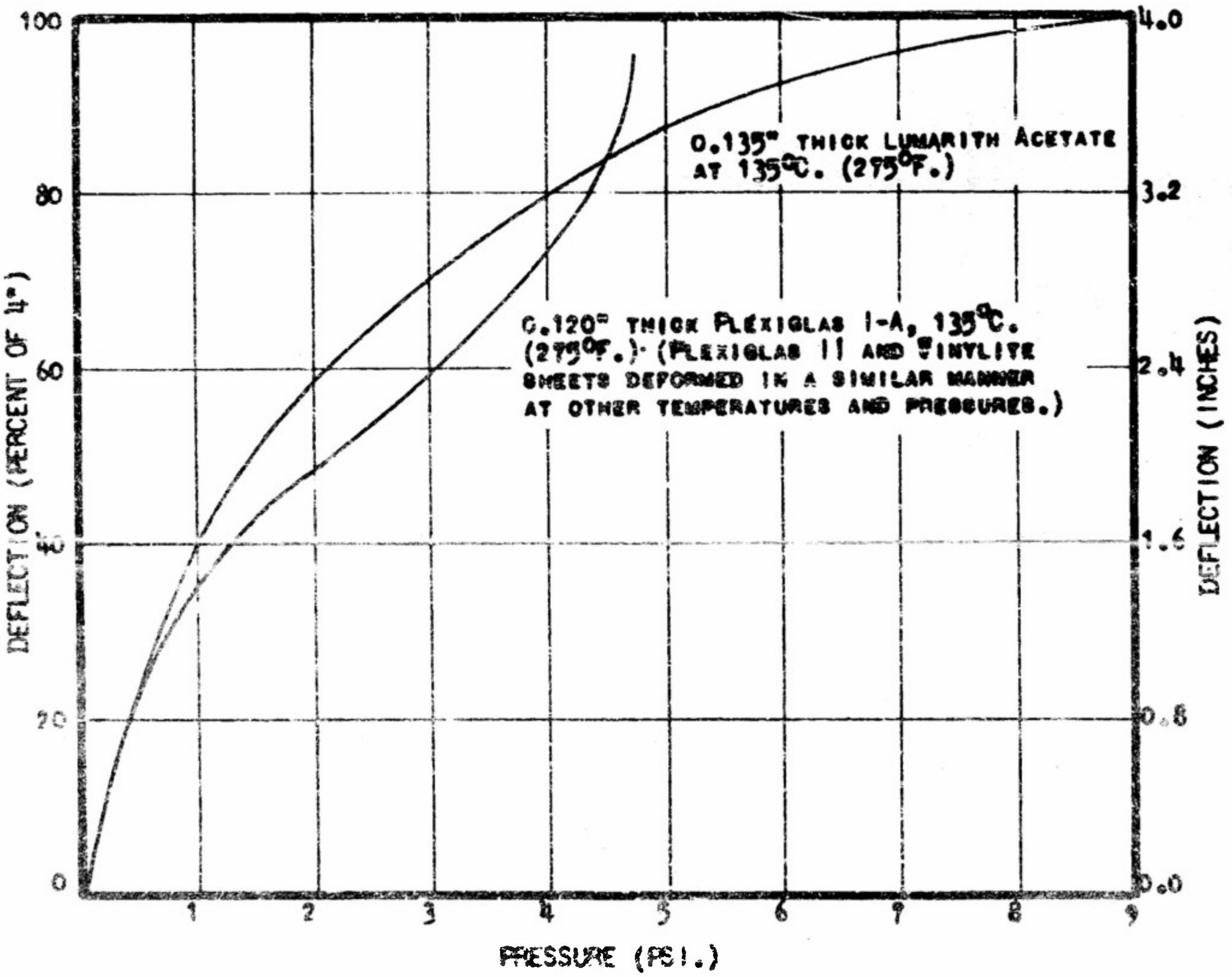


FIGURE 34. CHANGE OF DEFLECTION OF 8" DIAMETER SPHERICAL SECTION VS. PRESSURE
(PRESSURE MANUALLY CONTROLLED TO PRODUCE A UNIFORMLY INCREASING DOME HEIGHT)

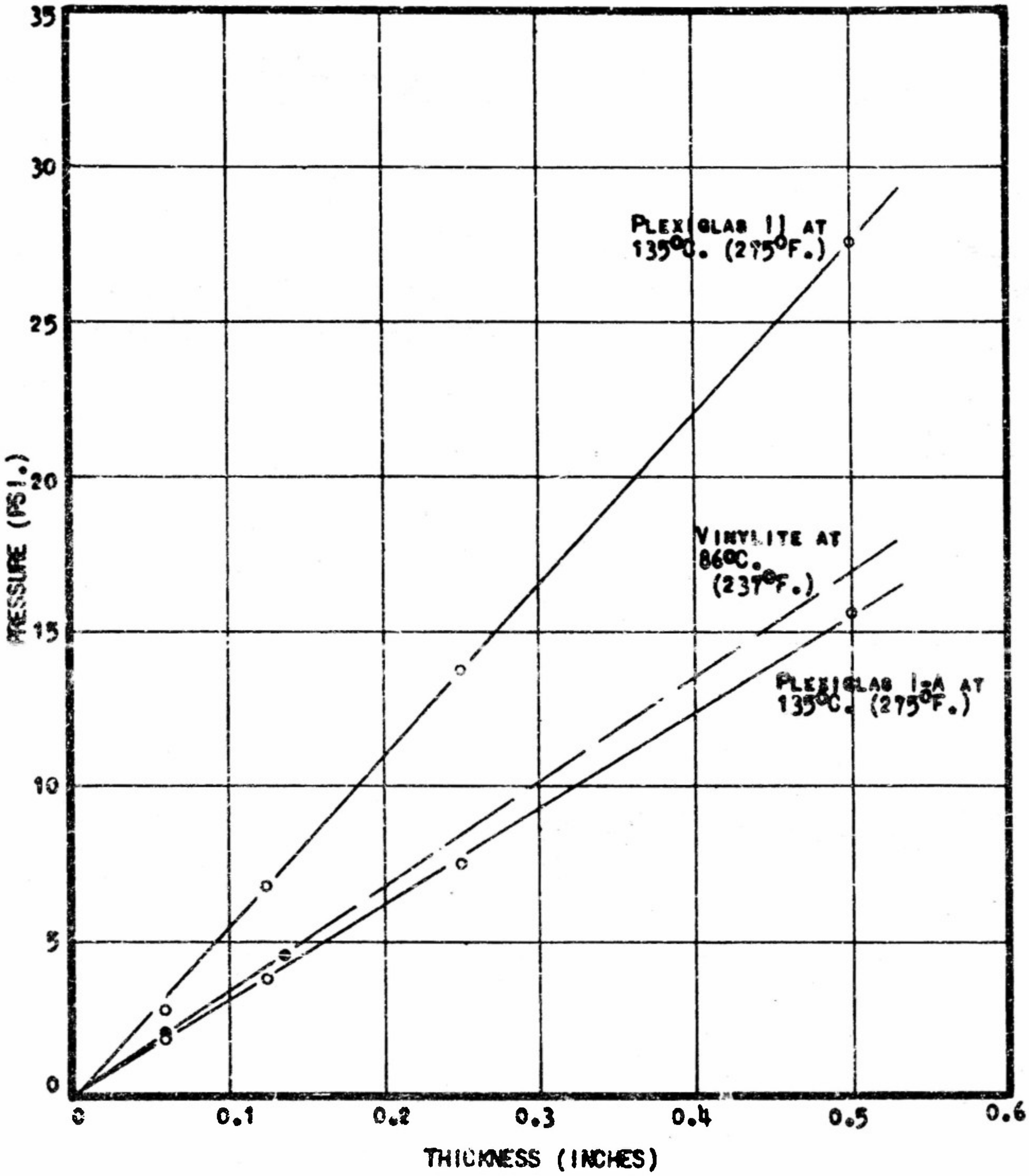


FIGURE 35. CONSTANT AIR PRESSURE REQUIRED TO FORM APPROXIMATE 8" DIAMETER HEMISPHERES AT THE INDICATED TEMPERATURES VS. THICKNESS OF PLASTIC SHEETS